

**PASSING ZONE BEHAVIOR AND SIGHT DISTANCE  
ON RURAL HIGHWAYS  
EVALUATION OF CRASH RISK AND SAFETY UNDER  
DIFFERENT GEOMETRIC CONDITIONS**

**FINAL PROJECT REPORT**

by

Nathan Belz, Ph.D.  
University of Alaska Fairbanks

Kevin Chang, Ph.D.  
University of Idaho

for

Alaska Department of Transportation and Public Facilities

and

Pacific Northwest Transportation Consortium (PacTrans)  
USDOT University Transportation Center for Federal Region 10  
University of Washington  
More Hall 112, Box 352700  
Seattle, WA 98195-2700

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## Executive Summary

To determine the effect of horizontal curvature, vertical curvature, and guardrail on driver passing behavior, a combination of field data collection and a driving simulator in a controlled environment were used. Field sites were identified along areas of concern to the Alaska Department of Transportation and Public Facilities: 1) Parks Highway (*Milepost 155–160*), Seward Highway (*Milepost 104–113*), and Sterling Highway (*Milepost 145.5–150.5*). Data were collected in the form of video in one passing zone in each these segments (totaling 165 hours), processed, and used to inform the development of the driving simulator. Driving participant testing was conducted in a simulated environment that replicated the identified sections of the two-lane rural highway in the state of Alaska.

The results of the field study showed that on all three highway segments (Parks, Seward, and Sterling), the average speed of passing vehicles was approximately 10 mph over the posted speed limit. The average initial speed of the vehicles being passed was approximately 2 mph over the speed limit. Standard deviations for both passing and impeding vehicles ranged from 3 mph to 7 mph. This aspect to driver behavior has significant implications for design of passing zones, as the American Association of State Highway Transportation Officials (AASHTO) and Manual on Uniform Traffic Control Devices (MUTCD) standards assume that the passing vehicle's speed does not exceed the posted speed limit. The field study revealed a significant number of "early start" and "late finish" passes, where a portion of the passing maneuver occurred outside of the designated passing area. The rate of early-start passes was higher for the Parks Highway segment, while the rate of late-finish passes was higher for the Seward Highway segment. Early-start and late-finish passes tended to occupy the opposing lane for more time than passes that were compliant and occurred completely within the confines of the passing zone.

Seventy-two participants were recruited and tested in the driving simulator at the Idaho Visual Performance Laboratory. The results of the simulator study showed that both horizontal and vertical curvature have significant effects on the characteristics of passing maneuvers including the speed of the passing vehicle, the total time and distance of the maneuvers, and the distance between the passing vehicle and the impeding vehicle at the initiation and termination of the maneuvers. Though geometry has an effect on passing choice and passing maneuver characteristics, it has no significant effect on safety outcomes of passes (in terms of total time to collision). Presence of guardrail does not affect the number of passes or the safety outcomes of passes but does affect the ability of drivers to avoid a collision when another vehicle is in their lane. Since a guardrail has a negative impact on safety (i.e., some would-be run-off-the-road crashes are converted to more severe head-on collisions), additional safety precautions such as signage (MUTCD 2B.28 and 2C.45) may be warranted.

## CHAPTER 1. INTRODUCTION

The Alaska Department of Transportation and Public Facilities (AKDOT&PF) and the University of Alaska Fairbanks (UAF) have identified a critical need to assess the current standards for passing zone requirements on two-lane highways in the context of horizontal and vertical alignment configurations. This project, which addresses that need, provides a better understanding of drivers' passing behavior under varied geometric conditions and how degree and mix of curvature influence driver behavior. The project's findings improve upon current American Association of State Highway Transportation Officials (AASHTO) guidelines and offer state Departments of Transportation (DOTs) better criteria for designing and evaluating geometric roadway configurations to improve the safety and efficiency of traffic operations. More specifically, this project seeks to improve the current standards on which the decisions to provide or not provide passing zones in a particular context are based.

### 1.1. Background

On rural two-lane roadways, a passing maneuver occurs when one vehicle overtakes a slower-moving vehicle by occupying the lane used by opposing traffic for some amount of time. For this passing maneuver to be accomplished, the driver of the faster vehicle must be able to see a sufficient distance ahead to make an informed and safe decision about whether there is enough distance and time to complete the passing maneuver without affecting the oncoming vehicle or the vehicle being passed. Since the passing maneuver requires both a transition into the opposing lane and then a return to the original lane of travel, additional sight distance is needed when compared with stopping sight distance. Drivers' passing judgment can be influenced by complex and curvilinear geometric alignments (e.g., combined horizontal and vertical curves) along with the presence of guardrail.

In 2008, more than 27% of fatal crashes occurred at horizontal curves (FHWA, 2010). Due to the predominance of horizontal curves on typical rural roads, a higher percentage of fatal curve-related crashes occur on rural roads, particularly on two-lane roadways; the fatality rate on rural roads is typically more than twice the rate on urban roads (AASHTO, 2011). Of all fatal crashes that occur on two-lane rural highways, about 20% are head-on collisions, with passing being the main cause of this type of crash (Persaud et al., 2004).

The Federal Highway Administration (FHWA) has reported that 25% of all fatal crashes occurring on two-lane rural highways are associated with horizontal curves (FHWA, 2014). This percentage is three times higher than the average crash rate of other U.S. highway systems, such as interstates and multilane highways. Fatal Analysis Reporting System (FARS) statistics indicate that 18% of head-on collisions occur on two-lane rural highway systems, and that 23% of all head-on crashes on two-lane rural highways occur when a driver is negotiating a horizontal curve (FHWA, 2016). A two-lane rural roadway with limited opportunities for drivers to execute passing maneuvers due to limited gaps between oncoming vehicles causes a reduction in capacity and level of service. A limited number of passing opportunities motivates some drivers to make risky passing attempts either late in a passing zone or on a portion of the road not intended for passing (see Figure 1.1). This safety concern increases on two-lane rural highways, which have varying geometric configuration (i.e., horizontal curves, vertical curves, compound curves, or a combination of these).



**Figure 1.1** A pick-up truck making a passing maneuver in a “double-yellow” segment on the Parks Highway near Trapper Creek, Alaska

In part, sight distance and passing requirements are affected by a persons’ ability to see an opposing vehicle and being able *to be seen* by the opposing vehicle, the driver of which is required to judge the speed and closing rate of the oncoming vehicle and make a defensive move if necessary. This passing maneuver is often considered one of the most complex maneuvers that can be made on a two-lane road or highway (McKnight & Adams, 1970), and the issue of sight and perception during passing maneuvers occurs on both horizontal and vertical curves.

However, a road segment with too few opportunities for drivers to execute a passing maneuver causes lengthy platoons and a reduction in capacity and level of service. Lengthy platoons are of particular concern on roads in Alaska such as the Seward, George Parks, and Richardson highways, National Highway System routes that are predominantly two-lane rural highway systems and are the only connections between some rural communities. In addition to having dynamic horizontal and vertical curve combinations (changing curve geometries), these highways have very high traffic loads, particularly in the summer months, when the formation of platoons is quite common. Extended periods of daylight during summer and extended periods of darkness during winter also create problems that involve both sight and human behavior issues.

Other factors that seem to affect available sight during a passing maneuver include the presence of guardrails, lighting conditions, amount of traffic, curve orientation, and the surrounding vegetation and landscape. The surrounding environmental, road, and weather conditions may affect a driver’s ability to identify whether a vehicle is in the opposing lane or the same lane, or the rate at which the vehicle is approaching. It is apparent that certain combinations of curve radius, length of curve, differences in grade, and type of transition design make it more difficult to judge the opportunities in which a passing maneuver is safe. It has generally been assumed that there are interactions between the safety effects of horizontal and vertical alignment combinations, but limited research exists to document these effects or demonstrate them in a form that can be used for safety prediction (FHWA, 2014).

## **1.2. Research Objective**

The objective of this research project was to examine how roadway geometry and roadside features such as guardrails affect driver passing maneuvers along rural two-lane highways. The main concerns addressed were how radius size, traffic level, and curve orientation (i.e., left versus right) affect passing and evasive maneuvers of drivers on horizontal and vertical curves.

The complexity of the myriad factors that contribute to the safety and efficiency of passing maneuvers makes the use of a driving simulator particularly advantageous. By controlling the driving environment, variables of most concern can be studied without being confounded by other, potentially less important, factors.

Real-world highway sections in the State of Alaska were utilized as reference sources since safety concerns along these sections had previously been documented. These sections included:

- Seward Highway (Milepost 104 to Milepost 113);
- Parks Highway (Milepost 154 155 to Milepost 160); and
- Sterling Highway (Milepost 145.5 to Milepost 150.5).

This study was conducted in a virtual driving environment using a driving simulator and using passing maneuver data collected in the field. For the simulation, a model of the roadway alignment along with a standardized traffic scenario was created. Participants were hired to drive both northbound and southbound along the simulated alignments, and each participant drive was followed by a questionnaire which collected socioeconomic information and asked questions about the factors that influenced their passing decisions during the simulation exercise.

## CHAPTER 2. LITERATURE REVIEW

The literature review focused on three broad sections involved with this research:

- passing maneuvers on rural two-lane highways;
- sight distance and no-passing zones;
- geometric conditions and alignment as they relate to passing zones;
- the driving environment and human factors;
- roadside characteristics and configurations; and
- driving simulators (i.e., evaluation of passing maneuvers in a virtual environment).

### 2.1. The Passing Maneuver on Rural Two-Lane Highways

On two-lane rural roads, the passing maneuver is accomplished by the faster vehicle occupying the lane used by opposing traffic for some amount of time. For passing to be accomplished without interfering with an opposing vehicle, the passing driver needs to be able to see a sufficient distance ahead such that an informed and safe decision can be made about whether there is ample distance and time to complete the passing maneuver without impeding the oncoming vehicle or the vehicle being overtaken. Since the passing maneuver requires a transition into the oncoming lane, overtaking the slower-moving vehicle in the oncoming lane, and then a transition back into the appropriate lane of travel, more sight distance is needed to pass than to stop. The following assumptions, as described in AASHTO, are made concerning driver behavior when assessing operational efficiency of passing maneuvers (Glennon, 1970; Hassan et al., 1996):

1. the overtaken vehicle travels at a uniform speed;
2. the passing vehicle has reduced speed and trails the overtaken vehicle as it enters a passing area;
3. the driver spends some amount of time to perceive the clear passing area and to initiate the passing maneuver, i.e., a delayed start;
4. the passing vehicle accelerates during the maneuver, occupies the left lane at a speed 12 mph (miles per hour) higher than the vehicle being overtaken;
5. the perception-reaction time of a driver deciding to abort a pass and the headway between passing and passed vehicles during an aborted pass are 1 second; and
6. the vehicle returns to its own lane with suitable clearance length between it and an oncoming vehicle in the opposing lane with minimum clearance of 1 second between the passing and opposed vehicles.

Current design values shown in Table 2.1 (AASHTO, 2011) are based on field observations (Harwood et al., 2007) and on two theoretical models for the sight distance needs of passing drivers, which define a critical position in the passing maneuver beyond which the passing driver is committed to complete the maneuver. The first model (Glennon, 1970) assumes that the critical position occurs where the passing sight distance to complete the maneuver is equal to the sight distance needed to abort the maneuver. The Hassan et al. model (1996) assumes the location first occurring of either the Glennon Model or where the passing and passed vehicles are abreast and passing sight distance is the sum of the following four distances (AASHTO, 2011):

$$PSD = d_1 + d_2 + d_3 + d_4$$

Equation 1

where:

$d_1$  = distance traveled during perception and reaction time and initial acceleration;

$d_2$  = distance traveled while the passing vehicle occupies the left lane;

$d_3$  = distance between passing and opposing vehicle at the end of the maneuver; and

$d_4$  = distance traveled by an opposing vehicle (taken as  $2/3$  of  $d_2$ ).

**Table 2.1** Passing sight distance for design of two-lane highways

Design Speed (mph)	Assumed Speeds (mph)		Passing Sight Distance (ft)
	Passed Vehicle	Passing Vehicle	
20	8	20	400
25	13	25	450
30	18	30	500
35	23	35	550
40	28	40	600
45	33	45	700
50	38	50	800
55	43	55	900
60	48	60	1000
65	53	65	1100
70	58	70	1200
75	63	75	1300
80	68	80	1400

## 2.2. Passing Sight Distance Design Considerations

Current design criteria for passing sight assume that the driver's eye at a height of 3.5 feet can see an obstacle also at a height of 3.5 feet (AASHTO, 2011). This determination is based on the object being the height of a vehicle, where 4.35 feet represents the 15<sup>th</sup>-percentile of the current passenger car population from which 0.85 feet are subtracted to account for the portion of the vehicle that would need to be visible in order to be recognized by another driver (Harwood et al., 1996). This determination is assumed to account for nighttime driving conditions, since headlights can be seen from a greater distance than the distance of vehicle recognition needs during the daytime. An informal study of state DOT design guidelines across the United States revealed that California refers to an object height of 4.5 feet and Iowa refers to an object height of 2.0 feet for passing sight distance, but both states publish the AASHTO and the Manual on Uniform Traffic Control Devices (MUTCD) guideline distances as well.

For horizontal curves, there is need for a clear sightline on the inside of the curve. For vertical curves, design criteria are applicable only to crest curves, as most sag curves will not impede sight distance. Note that the values in Table 2.1 are assumed sufficient for a *single or isolated pass only*. Additional consideration must be given in cases where the passing vehicle, the vehicle being passed, or both of the vehicles are trucks, as longer sight distances may be required (Harwood & Glennon, 1989).

### 2.3. No-Passing zones

Passing sight distance determines the passing zones and no-passing zones on rural two-lane highways. These zones are determined based on standards described in the MUTCD. Passing zones are established where there is sight distance greater than the prescribed limits in the MUTCD. For example, MUTCD guidelines for a rural two-lane highway having a posted speed limit of 55 mph or an 85<sup>th</sup>-percentile speed of 55 mph (whichever is greater) require a passing sight distance of 900 feet, meaning that if the sight distance drops below this threshold due to any obstruction, it marks the start of the no-passing zone. These values, shown in Table 2.2, have been updated from the previous edition of the AASHTO *A Policy on Geometric Design* (2004), also known as the *Green Book*, and are based on AASHTO’s decision regarding sight distances for a rural road avoidance maneuver involving speed, path, or direction change. The values presented in Table 2.2 are based on different operational assumptions than those presented in Table 2.1.

Of concern is that Farah (2013) determined that during a passing maneuver, approximately 42% of the time is consumed by reaching the “point of no return.” This percentage is in contrast to the 33% of time assumed in the AASHTO standard. Further, drivers still tend to pass other drivers even if the speed of the vehicle being overtaken is greater than the speed limit (Bar-Gera & Shinar, 2005). In addition, if warning is not provided at no-passing zone areas, there is some likelihood of increased crash rates (El-Zarif et al., 2002).

**Table 2.2.** AASHTO minimum passing sight distance for no-passing zone markings

85 <sup>th</sup> -Percentile Speed or Posted/Statutory Speed Limit (mph)	Minimum Passing Zone Length (ft)
20	400
30	550
35	650
40	750
45	800
50	800
55	800
60	800
65	800
70	800

Since 1940, several models have been developed to determine minimum passing zone requirements. These models resulted in the development of manuals and associated criteria, but several types of research have been carried out regarding the comparison of the models presented in these manuals. In a comparison review of passing zone guidelines between the MUTCD and AASHTO, some studies concluded that the current passing sight distance values in the MUTCD and AASHTO are very low. For example, the minimum length of a passing zone at 400 feet has unknown origins (Staplin et al., 2001). Another study published by the Transportation Research Board concluded similarly, that the reason for selection of passing sight distance values in the

MUTCD is not known. However, AASHTO considers several assumptions with regard to passing maneuvers, driver safety, and measurement on sections with regular traffic flow in their models (Hassan et al., 1995).

A large percentage of drivers can be represented by AASHTO's passing sight distance model, and it is based on the "delayed beginning and hurried return" assumption, which means that the passing car accelerates into the left lane at a speed 12 mph or higher than that of the overtaken car. Polus et al. (2000) indicated that the AASHTO sight distance model is adequate for car-car passing, as the values are a little higher than required, but for a car passing a truck, the values are not sufficient. Recent research comparing field data and passing sight distance criteria from AASHTO and MUTCD found that the values mentioned in these documents are consistent with field data collected from the states of Missouri, Pennsylvania, and Texas, and the use of current standards are recommended for marking no-passing zones (Harwood et al., 2010).

Though similar, the values presented in the most recent edition of the *Green Book* differ from those in the most recent edition of the MUTCD (FHWA, 2012), as shown in

Table 2.3. AASHTO recommendations (Table 2.2) do not exceed 800 feet for speeds in excess of 45 mph, while values given in the MUTCD are closer to those assumed for deciding sight distance on a rural road. Harwood et al. (2007) state that the minimum sight guidelines are a compromise between the distance that would be required for a *flying pass* (i.e., where the passing vehicle is not required to slow down before initiating the passing maneuver) and a *delayed pass* (i.e., the passing vehicle must decelerate to the speed of the vehicle being passed and then accelerates once initiating the passing maneuver). Passing sections shorter than those presented are not presumed to make a significant contribution to the operational efficiency of a two-lane roadway (AASHTO, 2011).

Locating no-passing zones in the field can be accomplished using several methods such as:

1. the Walking Method,
2. the Eyeball Method,
3. the Speed and Distance Method,
4. the Single Vehicle Method,
5. the Multi-Vehicle Method, and
6. the GPS Method.

These methods are briefly outlined here and discussed in detail in the *Traffic Control Devices Handbook* (Seyfried, 2013).

**Table 2.3** MUTCD minimum passing sight distances for no-passing markings

85 <sup>th</sup> -Percentile Speed or Posted or Statutory Speed Limit (mph)	Minimum Passing Zone Length (ft)
25	450
30	500
35	550
40	600
45	700
50	800
55	900
60	1000
65	1100
70	1200

The Walking Method requires that two persons walk the centerline of a roadway with a rope or chain stretched between them corresponding to the appropriate no-passing length for the given roadway speed. A no-passing zone is located when a target situated at a height of 3.5 feet can no longer be seen by the rear person, and ends when the target comes back into view.

The Eyeball Method requires that the section of road be driven in a vehicle by a person, presumably trained and experienced. The driver locates visually, and by judgment, where a no-passing zone should begin and end.

The Speed and Distance Method requires that the beginning location of a no-passing zone be estimated initially. The speed of a receding vehicle is then recorded along with the amount of time it takes for that vehicle to travel from the initial no-passing location until it disappears from view. This process is iterated until the point relating to the minimum passing sight distances is located.

The Single Vehicle Method utilizes a vehicle outfitted with a Distance Measuring Instrument (DMI). A driver navigates through a curve until there is sufficient sight distance for passing, corresponding to the end of the no-passing zone. From this point, the DMI is used to measure a distance equal to the minimum passing sight distance, which marks the beginning of the no-passing zone.

The Multi-Vehicle Method most commonly uses two vehicles outfitted with DMI. Using two-way radios, drivers of both vehicles traverse the roadway while maintaining the required minimum passing sight distance according to the DMI. The beginning and end of the no-passing zone are located where the lead vehicle disappears and reappears from the lagging vehicle's view. Previous research has shown that the Single Vehicle Method is generally more accurate than the Multi-Vehicle Method (Brown & Hummer, 2000).

The GPS Method relies on one of several techniques to obtain GPS coordinates of the road centerline. These coordinates are used to develop a geometric model of the road surface. Sight distances are then calculated using the three-dimensional model from which no-passing zones can be located based on minimum sight distance criteria. Though this method is more objective and does not rely on the experience or judgment of the evaluator as in the previously discussed

methods, it is heavily reliant on the accuracy of GPS. That being said, existing research shows that there can be large discrepancies, and thus this method has been used mostly to identify locations for sight deficiency consideration and not specifically for marking no-passing zones (Namala & Rys, 2006; Williams, 2008).

#### **2.4. Geometric Conditions and Alignment**

The physical characteristics of a road can play a significant role in the way in which a driver perceives and reacts to the surrounding environment. With reference to roadway geometry, horizontal and vertical curves, rather the combination of the two, can lead to erroneous perception of the alignment features. Smith and Lamm (1994) proposed that a combined crest and horizontal curve would make a driver perceive the horizontal curve to be sharper than it actually is, while a combined sag and horizontal curve would cause the driver to perceive the horizontal curve to be flatter than it actually is. This theory is known as the *driver perception hypothesis*, the supposition being that a driver would be inclined to adopt a lower or higher speed than if the horizontal radius were on a flat grade, which is of particular concern on a sag combination where the driver would perceive the curve to be flatter and adopt a higher, potentially unsafe, operating speed. The driver perception hypothesis has been validated by later studies using computer visualization techniques and qualitative evaluations of subjects on the visual representation of a road scenario (Bidulka et al., 2002; Hassan & Sayed, 2002). In general, speed reductions tend to be greatest for crest combinations and in the presence of horizontal curves with smaller radii (Hassan & Sarhan, 2012). Other studies, such as those conducted by Perco (2008) and Cardoso et al. (1998) suggest that the alignment does not necessarily influence the maximum operating speed, but rather the curvature change rate, representing the character of the road alignment. Studies have addressed where drivers tend to focus their attention while navigating curves (Zhao et al., 2011), indicating that the central part of the curve is a critical location when trying to maintain lane position and that drivers' attention to the roadway increases as they approach the apex of the curve. Advance curve warning signs have proven an effective tool at informing drivers of problematic curves and improving safety at those locations (Shinar et al., 1980). In addition, the natural reduction in speed on horizontal curves has shown to be beneficial in terms of collision risk (Bella & D'Agostini, 2010).

Though these previous studies provide insight into the way that drivers behave while negotiating curvilinear roadway alignments, they do not specifically address the nature of passing behavior under these conditions. It appears that there are certain combinations of curve radius, length of curve, differences in grade, and type of transition design that make it more difficult to judge the opportunities for a safe passing maneuver. It has generally been assumed that there are interactions between the safety effects of horizontal and vertical alignment combinations, but limited research exists to document these effects or demonstrate them in a form that can be used for safety prediction (FHWA, 2014). Further, the influence of curve orientation on a driver's ability to recognize suitable gaps in traffic to execute a passing maneuver has not been adequately addressed. This is to say that if the lane of travel is located on the inside of the curve versus the outside of the curve, the driver might have more or less difficulty seeing and judging potential gaps in the opposing stream of traffic.

## **2.5. Driving Environment and Human Factors**

Human behavior dictates the type of driver interactions, inherently affects driving task and load, and is an important consideration in traffic operations and road safety. Passing sight distance criteria for vertical or horizontal curves have not historically included factors that relate to variations in driver performance and capabilities (Neuman, 1989; Fambro et al., 1997), particularly those in an aging driver population. Other issues with the current criteria include (1) the fact that passing sight distance is based largely on old, perhaps outdated, field data of only passenger cars; (2) questionable speeds and maneuver types involved while passing; (3) no consideration of drivers who are not “committed to pass” and will abort a passing maneuver; and (4) the incorporation of a compromise between “flying” and “delayed” passing maneuvers (Transportation Research Board, 2008). Though some simulator studies have found that road curvature does not significantly impact variables such as passing duration and distance, findings do not consider the likelihood of initiating a maneuver or the safety of doing so (Farah, 2013).

Traffic conditions, such as the formation of platoons and the availability of gaps, have been shown to influence a driver’s passing behavior. Traffic platoons can be impacted and formed by certain geometric configurations (Farah et al., 2009). The coinciding traffic volumes then change the nature of following gaps and can influence the way in which people look for passing opportunities and execute passing maneuvers (Bella, 2013) and potentially increase the risk of rear-end collisions. From an operational standpoint, it is important to provide enough opportunities for drivers to pass slower-moving vehicles in order to maintain an adequate level of service. The length of a passing zone can increase the likelihood of passing, but only up to a length of about 3500 feet (Moreno et al., 2013). Driver characteristics are an important consideration in the nature of passing behavior. Some studies, such as that by Bekhor and Toledo (2007), show that some drivers, particularly those that are considered “patient and careful,” require significantly longer gaps to attempt a passing maneuver.

Limited visibility conditions, such as those caused by inclement weather or during nighttime driving, might also be of concern. Though some studies suggest that driver behavior is significantly affected when driving at night versus day (Calvi & Bella, 2014), speeds during nighttime negotiation of curves are not significantly different from those during daylight (Bella et al., 2014), though the authors note that the horizontal curves simulated in the study were of “sharp radii.” The lack of visibility in certain environmental conditions (e.g., fog) causes some drivers to follow too closely, while other drivers increase their following gap distance compared with their distance in normal visibility conditions (Broughton et al., 2007). These behaviors have direct implications for the availability of gaps in which a driver can perform a passing maneuver, and influence the way in which a passing maneuver is performed.

## **2.6. Roadside Characteristics and Configurations**

Anecdotally, factors that seem to affect available sight during a passing maneuver include the presence of guardrail and the surrounding vegetation and landscape. Speed and lateral placement of drivers were not affected by roadside configurations (i.e., presence of trees and/or barriers such as a guardrail), rather only the alignment and profile of the road (Bella, 2013). Delineation on and advance warning before curves are effective ways of keeping vehicles at an appropriate speed through curve negotiation (Charlton, 2007). Again, though studies have addressed the way

in which roadside features affect driver behavior, there is little evidence to suggest how these features influence a driver during a passing maneuver.

## **2.7. Driving Simulator Applications**

In the real world, changing a driver's ability to pass by re-marking passing zones based on engineering judgment, time of day, or season is not realistic. Driving simulators are a very useful way of studying driver perception of roadway features and environments in a controlled environment. The virtual environment can be created to replicate an original highway and test a driver under various conditions. Primary advantages include low cost, ease of data collection, safety for test drivers, and being able to interact easily with the participants after the experiment has concluded to ascertain their perspectives and qualitative evaluations of the experience (Bella, 2009; Lamm et al., 1999; Zakowska, 1999). The driving simulator can generate data about many driving parameters such as lane position and acceleration-deceleration, and this data can be analyzed for research. Several studies have shown that data obtained from a driving simulator are a reliable source of information and similar to data that could be collected from the field.

Moreover, these data can be used to assess a driver's behavior and passing maneuvers (Farah, 2013; Hillel & Shinar, 2005; Francesco, 2014; Bella & D'Agostini, 2010).

A study on deriving the tendency of a driver to pass another vehicle revealed that mental load is the prime contributor for passing maneuvers (Bar-Gera & Shinar, 2005). This conclusion can be supported by the explanation in AASHTO that drivers need to process visual information such as geometric information, car speed, weather, and visibility. Increased amounts of information processed by a driver require more time in making a decision, and if there is an error in one or more details processed by the driver, the driver must terminate the passing movement, if possible, or the likelihood of a vehicle crash will increase.

A study of the driver perception hypothesis, where the perception of three different types of curves—namely flat horizontal curves, horizontal curves with vertical sag, and horizontal curve with vertical crest—by the driver was studied by measuring the change in speed and lateral position. The results indicated that there is no significant reduction in speed and no major change in lateral position for flat horizontal curves and horizontal curves with vertical sag, while the horizontal curve with vertical crest produces speed reduction and change in lateral position. From the results, it was concluded that horizontal sag curves are safer than horizontal crest curves, as driver perception on sag horizontal curves exhibits similar results with flat horizontal curves, whereas crest horizontal curves resemble sharper curves (Francesco, 2014).

A safety evaluation study was carried out by Bella to assess the risk of collision with respect to traffic volumes. The time to collision, which was analyzed for rear-end collisions, implied that as the traffic volume increased, the risk of rear-end collisions increased. The detailed analysis concluded that geometry has no effect on the risk of rear-end collisions; hence, whether it is a straight section or a curvilinear road, the amount of traffic is the key factor influencing time to collision on two-lane highways (Bella & D'Agostini, 2010). In an effort to evaluate the effects of the presence of a shoulder and guardrail on vehicle speed and position on horizontal curves, a study by Francesco (2013) revealed that vehicle speed is greatly influenced by horizontal curves, while lateral position is affected by the presence of shoulder and guardrail.

A number of studies have validated driver behavior in rural environments in driving simulators with real-world field data (Bella, 2008); that is, average speeds at point locations along a test

section in the simulator have been compared with corresponding points on the actual road segment. Though speed comparisons show that a driver's behavior in the simulator is generally representative of behavior in a real driving environment (Meuleners & Fraser, 2015), speeds on long unconstrained sections of roadway, such as long tangents, tend to be significantly higher in the simulator (Boer et al., 2000; Simsek et al., 2000). However, this finding is countered by other research which suggests that speeds are faster in an instrumented car in a real-world environment than in the simulator when a driver is exposed to complex situations such as dynamic curves and intersections where deceleration and acceleration are necessary (Godley et al., 2002). In addition, simulator driving speeds more closely matched real-world speeds under high-resolution, narrow-field-of-view simulated conditions, while lane position of the simulator drivers was closer to that of real-world drivers under low-resolution, wide-field-of-view simulated conditions (Jamson, 2000).

This literature review did not find any previous research related to either passing maneuvers on horizontal curvature or the assessment of passing maneuvers along a real-world alignment in a virtual environment. Filling this knowledge gap is a keen point of interest for this research.

## **2.8. Research Needs**

Based on the literature discussed in the previous sections, five primary topics for research still exist and warrant further study:

1. The presumption that distance at which headlights can be seen negates the need for consideration in passing sight distance, as it is larger than the distance to recognize a vehicle as such. The difference between the height of headlights (2.0 feet) and the assumed vehicle height for passing sight distance (3.5 feet) is considerable, and the recognition of headlights is contingent upon roadway configuration and the roadside environment.
2. The assumed speed and acceleration values in the AASHTO guidelines are known to be invalid and out of date.
3. The characteristics of passing behavior on horizontal curves, vertical curves, and curve combinations are likely different from those on flat tangents. Though much research points to the way in which drivers behave on curvilinear alignments, there is little or no research to support how passing maneuvers vary on these types of segments.
4. The influence of roadside elements and environmental conditions on driver behavior in general has been studied, but not explicitly how these elements affect passing sight and passing behavior.
5. Passing behaviors in a simulated environment have not been validated with passing behaviors in a real-world environment.

## CHAPTER 3.0 METHODOLOGY

This chapter describes the methodology used to test and measure driver passing behavior. The background section describes the general concept of the methods used and is followed by a discussion of the procedures used for field data collection. Then a section on the functions and operations of the driving simulator is provided. Finally, the development of the different scenarios is explained, and the experimental design parameters of the simulated traffic and procedures for laboratory data collection are discussed.

### 3.1 Background

To determine the effect of horizontal curvature, vertical curvature, and guardrails on driver passing behavior, a combination of field data collection and a driving simulator in a controlled environment were used. Field sites were identified along areas of concern to the Alaska Department of Transportation and Public Facilities (AKDOT&PF). Data were collected at these sites and used to inform the development of the driving simulator. Driving participant testing was conducted in a simulation environment that replicated the identified sections of two-lane rural highway in the state of Alaska. Each participant conducted, at most, one session, driving for no more than 50 minutes. After each participant concluded the session, the person responded to questions from the debriefing form related to the study.

### 3.2 Field Data

Three segments of highway were identified as locations of interest based on historic crash records and input from AKDOT&PF: (1) Parks Highway (*Milepost 155–160*), Seward Highway (*Milepost 104–113*), and Sterling Highway (*Milepost 145.5–150.5*). A summary of fatal and major injury crashes for the period 2001 through 2008 for these locations can be found in Appendix A.

Several field visits were made to each site to identify potential segments for field data collection. This decision was aided by video that was obtained by mounting a camera to the inside of a windshield while driving the segments to obtain driver point of view. These videos were also used for reference in the development of the driving simulator tiles, as discussed in Section 3.3 of this report.

#### 3.1.1. Data Collection

One passing zone section was selected from each of the identified segments of highway for field observation (see Street View Imagery obtained from Google Maps in Figure 3.1 through Figure 3.3). The passing sections were selected based on ease of access and availability of vantage points for video cameras to capture real-world passing behaviors. For in-field collection of these passing maneuvers, three video cameras (see Figure 3.4 for typical camera setup) were used to capture vehicle position and time throughout each of the selected passing zones. The cameras used were Ten and Two Travel Time Monitors purchased from L2 Data Collection Solutions. These particular cameras were selected for four reasons:

1. relatively low cost compared with other proprietary and specialty camera systems;
2. ability to run on a rechargeable 18Ah battery with multi-day capacity for uninterrupted footage in locations where a permanent power source is not available;
3. adjustable field of view to account for setup at varied distances from edge of roadway depending on roadside topography and vegetation; and
4. a digital video recorder (DVR) is used with up to 48 hours of video storage capacity.

The field of view of each camera was overlapped so that vehicles could be tracked continuously through the entire passing zone (see Figure 3.5). When available, cameras were mounted directly to trees of adequate size or telephone poles using buckle straps. At field segments or locations where this option was not available, a 3-inch PVC conduit with mounting brackets and guy-wires was affixed to the ground using a standard tent peg or tethered to a nearby object using straps. Each camera was located such that it would not be visible to the common passerby or untrained eye. Video was only collected on fair-weather days when no environmental or weather conditions would affect visibility or the condition of the pavement.

Reference points to be used for trajectory extraction were physically placed on the side of the roadway at 100-foot spacing using temporary marking paint. A series of preliminary field studies indicated that reference points at a spacing of less than 100 feet were too small for accurate vehicle trajectory digitization and data extraction. The reference points were also enhanced digitally during post-processing for better visibility.



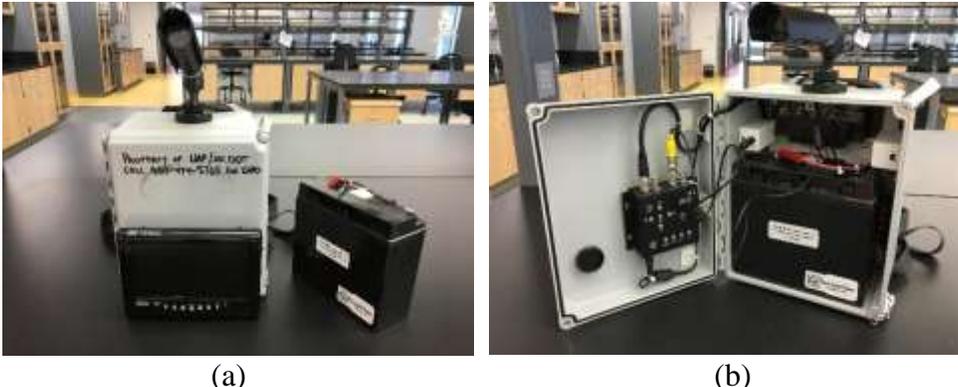
**Figure 3.1.** Parks Highway northbound at (a) beginning of passing zone and (b) end of passing zone at Milepost 159 on a right-oriented curve near Trapper Creek, Alaska



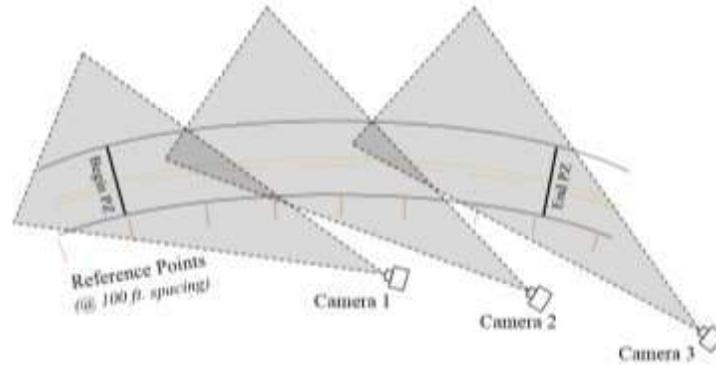
**Figure 3.2.** Seward Highway northbound at (a) beginning of passing zone and (b) end of passing zone at Milepost 105 on a left-oriented curve near Indian Valley, Alaska



**Figure 3.3.** Sterling Highway southbound at (a) beginning of passing zone and (b) end of passing zone at Milepost 148 on a relatively straight section near Anchor Point, Alaska



**Figure 3.4.** Camera setup showing (a) external view with LCD monitor and (b) internal view with DVR control and installed battery



**Figure 3.5.** Schematic of typical field data collection setup

### 3.1.2. Data Processing

Video files were collected at 30 frames per second and segmented into 1-hour periods for ease of processing and transferring later. These raw video files were first processed to eliminate files where very few or no cars were present in the frames. Once a final set of video was isolated, each 1-hour period was watched at 90 frames per second (three times the normal speed) to identify when passing maneuvers were executed. The timestamps corresponding to the initiation of a passing maneuver (Camera 1) were recorded and saved for processing later. A summary of the total processed video time and the number of passing maneuver observations can be seen in Table 3.1.

**Table 3.1** Field site summary statistics

	Parks Highway (1)	Parks Highway (2)	Seward Highway	Sterling Highway
<b>Site Characteristics</b>				
Beginning Milepost	159 NB		105 NB	148 NB
Observed Segment Length (ft)	3600		4000	2750
Passing Zone Length (ft)	2630		3100	1665
Horizontal Curve Orientation	Right		Left	n/a
Vertical Curve Orientation	Crest		n/a	n/a
Posted Speed Limit (mph)	65		55	55
<b>Field Data Characteristics</b>				
Total Video Collected (hh:mm)	42:35	36:45	44:29	40:22
Start Date of Collection (yyyy-mm-dd)	2015-06-26	2016-06-10	2016-07-22	2017-08-19
Total Video Processed (hh:mm)	20:00	18:00	25:00	14:00
Passing Maneuvers Observed	23	11	18	7

The previously recorded timestamps were then used to identify the series of frames from each video that coincided with a passing maneuver. Timestamp and position of vehicles were coded with a computer-aided script that uses a keystroke command to record time points at a resolution

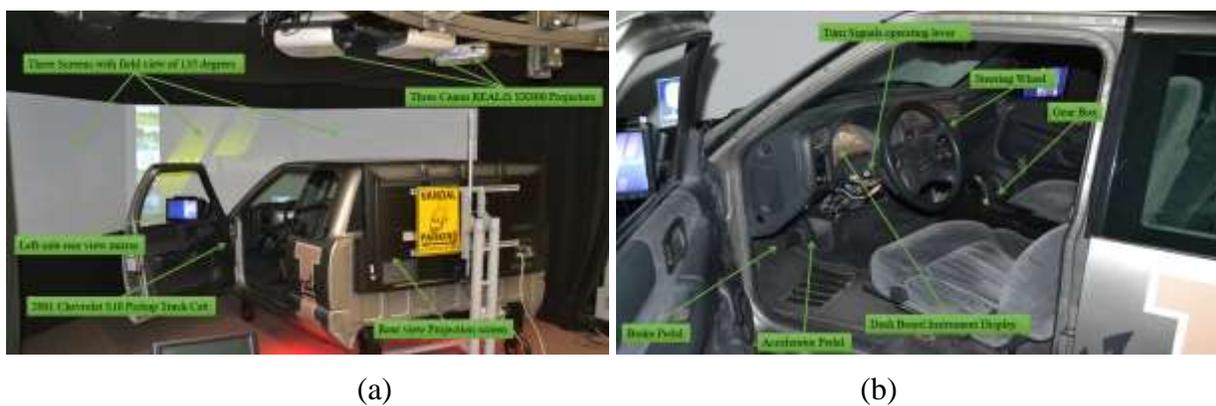
of 0.01 seconds. Considering frame rate and timestamp accuracy, the temporal error is limited only to that of coding by the analyzer. To minimize temporal coding error, two individuals extracted position and time from the data. Passing maneuvers of two vehicles were extracted by two individuals for each field site and compared to ensure that at least 95% match was achieved in the positional markings. If this match was not achieved, the trajectories were extracted again and then compared. This process was repeated until the match criteria were achieved. Once match was achieved for the initial six trajectories, the remaining passing maneuvers were extracted by a single individual. Having timestamps associated with the reduced data also allowed for discrepancies and isolated issues to be reexamined and rectified as needed.

Lateral vehicle position was recorded to the nearest quarter-point on the roadway at each 100-foot marker throughout the passing zone. A passing maneuver was considered initiated when the center of the passing vehicle crossed over the centerline of the roadway. In general, the initiation and execution of a passing maneuver were observed in Camera 1 and Camera 2, while the termination of the passing maneuver was observed in Camera 3 (Figure 3.1).

One significant limitation is that the distance traveled by the opposing vehicle and the distance between the passing vehicle and the opposing vehicle at the end of the maneuver were not always observable due to the camera position, particularly for late-finish passes. Additionally, because of the camera orientation, we were unable to see the initial gap size between the passing vehicle and the vehicle in the opposing stream at the initiation of the pass.

### 3.3 Driving Simulator

The driving simulator at the Idaho Visual Performance Laboratory (IVPL), shown in Figure 3.6, is a medium fidelity fixed-base driving simulator. The simulation software is National Advanced Driving Simulator (NADS) MiniSim version 2.0 installed on a Windows 7 workstation. The hardware is composed of cab-mounted controls for realistic user interaction; a single workstation for all simulation processing, data collection, and graphics rendering; and additional components for audiovisual output and to facilitate transmission of information between the primary hardware components.



**Figure 3.6.** Driving simulator (a) overall layout and (b) control panel

The cab for user interaction is from a 2001 Chevrolet S10 pickup truck. The vehicle controls are connected to the MiniSim via a Suzo-Happ model 95-0800-10k USB Game Controller Interface (UGCI). The steering wheel is the original steering wheel from the S10 pickup; it is self-

centering and has a 540-degree steering range. The brake and accelerator pedals are also original equipment from the S10 pickup and provide haptic feedback similar to the feedback of a normal automobile. An automatic gear selector from a 2001 Honda Civic was installed in the center console to give users a standard interface for gear selection.

The simulation visuals are displayed via a 7-channel display configuration. The first three channels are displayed by three Canon REALiS SX800 projectors, which project the front view of the simulation environment onto three 90-inch screens at a combined resolution of  $4200 \times 1050$  pixels. The three screens form three sides of an octagon centered at the projected eye-point of the simulation for a field of view of 135 degrees horizontally and 34 degrees vertically. The cab is positioned so the driver's eyes are at the projected eye-point of the simulation. The fourth video channel displays the dashboard instrument cluster, including a speedometer, tachometer, engine temperature, gear selection, and fuel gauge. This channel is displayed by a 10-inch liquid crystal display (LCD) screen with a resolution of  $1280 \times 800$  pixels that is mounted in place of the original instrument cluster. The final three channels display the rear view of the simulation. Eight-inch LCD screens with a resolution of  $800 \times 600$  pixels are mounted on the driver side and passenger side mirror housings of the cab. A 65-inch plasma screen with a display resolution of  $1280 \times 720$  pixels is mounted on the rear of the cab and is visible through the original center rear-view mirror.

The workstation contains a six-core Intel Core I7 processor running at 3.9 GHz, 32 GB of RAM, and two Nvidia video display adapters. A GeForce GTX680 GPU processes the three main screens, which are routed through a Matrox T2G-D3D-IF multi-display adapter, as well as the instrument cluster and the passenger side mirror. A GeForce GTX660TI GPU processes the driver side mirror and rear screen. Finally, a 4.1-channel audio system uses four speakers mounted in the cab doors and a subwoofer mounted behind the driver's seat to produce engine, environmental, and road noise.

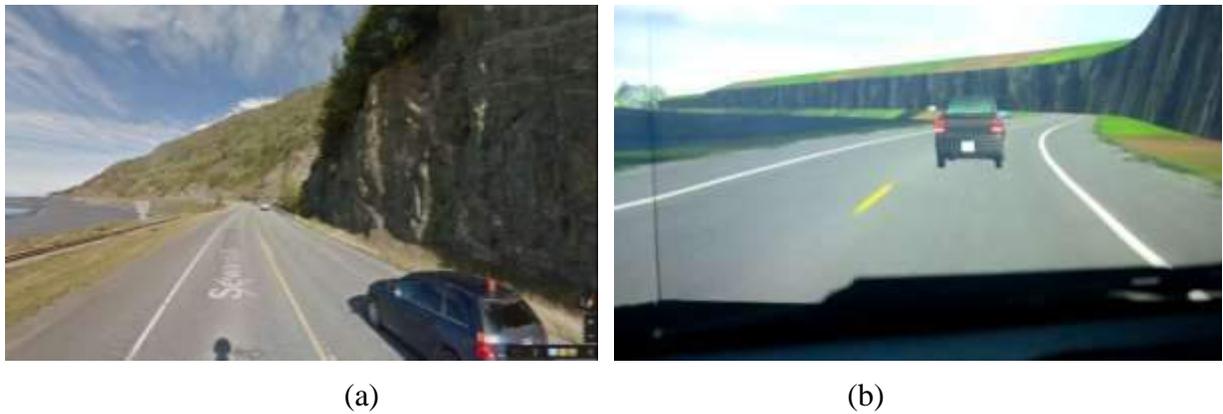
The MiniSim simulation software is a part of the driving simulation suite developed at the National Advanced Driving Simulator (NADS) and The University of Iowa, which also includes the Tile Management Tool (TMT) and Interactive Scenario Authoring Tool (ISAT) for simulation development. The MiniSim utilizes NADSDyna high-fidelity vehicle dynamics software to model vehicle dynamics in the simulation. During the simulation, MiniSim uses information from the terrain visual database, terrain logical database, and scenario to render the simulation. Additionally, the software records vehicle input, vehicle dynamics, and scenario-related variables at a collection frequency of 60 hertz.

### *3.3.1. Scenario Development – First Stage*

To develop the required scenarios for each participant, multiple software applications were used along with the MiniSim simulation program to test these scenarios. Every scenario was composed of multiple tiles that displayed the appropriate roadway geometries and the surrounding environment. These roadway geometries were based on the three real-world alignments of the Alaska Highway system.

Autodesk AutoCAD Civil 3D software was used to create the alignment, profile, and corridor for each test section based on as-built plans from the AKDOT&PF. The corridors consisted of a 51-foot-wide planar cross section projected along the alignment and profile. The corridors were exported from Civil 3D and imported into Autodesk 3ds Max.

In 3ds Max, an image texture was applied to the roadway, resulting in a 24-foot-wide paved roadway with a centerline and fog lines as well as six-foot paved shoulders with gravel and grass edges. For the first stage of the study, a dashed centerline (i.e., permitted passing) was provided for the entire roadway regardless of sight distance. The surrounding environment was then created in consultation with staff from the AKDOT&PF. The environment included a cliff and water body for Seward Highway, and forest, rolling highway, and mountains for the Parks and Sterling highways. Example comparisons between each simulated environment and Google Street View screenshots are shown in Figure 3.7 through Figure 3.9. Each road section with the surrounding environment was exported as a tile to be combined into a visual database by NADS Tile Management Tool (TMT) software. The surrounding environment was exported to Civil 3D as well for sight distance analysis. Finally, a 3ds Max script was used to extract the coordinates of the centerline of each section to be used for roadway logic and to calculate geometric variables for each track.



**Figure 3.7.** Seward Highway comparison of (a) actual highway and (b) simulated highway



**Figure 3.8.** Parks Highway comparison of (a) actual highway and (b) simulated highway



**Figure 3.9.** Sterling Highway comparison of (a) actual highway and (b) simulated highway

The tiles for each section were combined with each other and with background filler tiles in TMT. The exported visual databases were then installed into the MiniSim visual directory to be rendered during the simulation. Text files containing the centerline coordinates for each tile were combined and exported by TMT. The resulting logical databases were installed into the MiniSim directory to be used for roadway logic during the simulation.

Python scripts were developed to write the scenario files, which consist of information regarding the locations and characteristics of the vehicles, speed limit signs, and data collection triggers in the simulation. The scenario files were then opened in ISAT to visually inspect the object locations and verify that the Python scripts worked correctly. Finally, the scenario files were imported into the MiniSim directory. Each scenario was tested multiple times to verify the correct placement and behavior of scenario and environmental objects. The output data from the trial runs were also analyzed and validated before any data were collected.

#### Simulated Traffic

The simulated traffic needed to be condition-specific to encourage passing by each participant along the selected roadway sections. Traffic was initially simulated in the travel lane at 43 mph (per AASHTO guidelines) as well as in the opposing lane at 55 mph. The posted speed limit for all roadway segments was 55 mph. The same-lane traffic had a gap of one-quarter mile, which provided sufficient time and distance for a driver to initiate and complete a passing maneuver. The opposing vehicles were created at one-half mile distances along each track; a one-half mile gap has been shown to encourage passing on two-lane rural highways (Dixon, 2015).

#### Experimental Design

To evaluate the passing decision-making of drivers with varying geometric conditions, hired participants drove for about an hour in the simulator. Participants drove through different track combinations, once driving northbound or southbound, taking a break of 5 to 10 minutes, and then driving the opposite direction. Each drive was followed by a participant questionnaire that collected personal perspectives about type of driving (aggressive or passive) and socioeconomic information (age, sex, and years of driving experience).

The statistical experimental design of a Latin square was carried out to control for order effects in the experiment. In a Latin square design treatment, sections were assigned to rows and columns in such a way that each treatment occurred once. Table 3.2 shows an example of the experimental design used for this study. Each track was driven by eight participants.

**Table 3.2** Latin square experimental design (Stage 1)

Track Order	Tile Order						
Track 1	Seward (NB)	Parks (NB)	Sterling (NB)	Break	Sterling (SB)	Parks (SB)	Seward (SB)
Track 2	Parks (NB)	Sterling (NB)	Seward (NB)		Seward (SB)	Sterling (SB)	Parks (SB)
Track 3	Sterling (NB)	Seward (NB)	Parks (NB)		Parks (SB)	Seward (SB)	Sterling (SB)

### Data Reduction

Each session recorded about 1 gigabyte (1 GB) of data, which was stored in a data acquisition format. These data contained microscopic information related to vehicle dynamics, user input, and position, and were defined in accordance with SAE International recommended practices (SAE, 2015). Data related to vehicle dynamics included speed and acceleration. User input data included steering wheel angle, accelerator position, brake pedal position, turn signal position, and gear selector position. Position data included the vehicle’s coordinates, lane position, and following distance, as well as the coordinates of every vehicle in the scenario. All data acquisition files were converted into a hierarchical data format for data reduction.

A script was written using an IPython interface to extract data about attempted passes. Whenever the participant’s vehicle entered the oncoming lane, the identification of the vehicle being followed was recorded. When the participant’s vehicle returned to its own lane, the identification of the vehicle being followed was compared with the previous vehicle; if the vehicles were different, then the event was recorded as a pass. If the vehicles were the same, then the status of the turn signal at the initiation of the movement was checked. The event was recorded as an aborted pass if the signal indicated that the driver intended to move to the left lane, and the event was not recorded if the driver did not indicate that the lane breach was intended.

Several additional variables related to each pass attempt were either recorded directly from the raw data or calculated. These variables include the location of the participant’s vehicle at initiation and conclusion of the maneuver; distance to the impeding vehicle and oncoming vehicle at initiation and conclusion of the maneuver; total time and distance spent in the opposing lane; vehicle speed when abreast of the impeding vehicle; and time to contact with the oncoming vehicle at initiation and conclusion of the maneuver. The location of the vehicle at the time of initiation was then used to extract geometric data such as sight distance, slope, and horizontal and vertical curvature.

### *3.3.2. Scenario Development – Second Stage*

The second stage of the driving simulation experiment focused on the effects of guardrail and centerline striping on driver passing behavior. Results from the first stage were used to prioritize shorter sections of highway so more repetitions could be completed. The targeted sections were the Seward Highway (Milepost 109 to Milepost 112), Parks Highway (Milepost 158 to Milepost 160), and Sterling Highway (Milepost 149.5 to Milepost 150.5).

This stage also included a short experiment to test the effects of a guardrail on collision avoidance. Each participant encountered an opposing vehicle that was executing a passing maneuver and was in the participant’s travel lane. To avoid a head-on collision, the participant

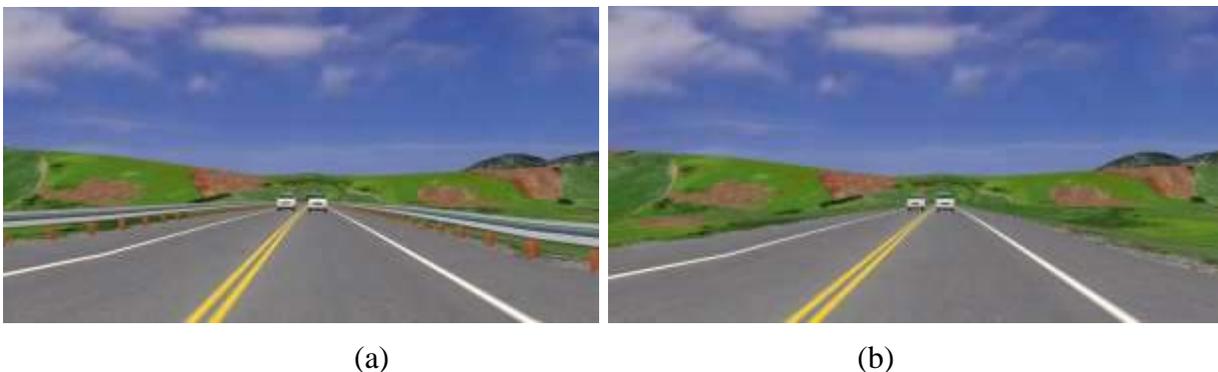
needed to move out of the oncoming vehicle's trajectory by moving toward the edge of the road. For half of the participants, the shoulder was clear (i.e., no guardrail was present); for the other half of the participants, the shoulder was not clear (i.e., guardrail on the shoulder).

The procedure for developing the simulation scenarios for the second stage was the same as for the first stage, with the additions of changing the centerline striping and adding a guardrail. Google Street View was used to identify the locations of the passing zones and guardrail sections. The appropriate image texture (striped for no passing, two-way passing, or one-way passing) was then applied to the roadway in 3ds Max to match the observed striping. Guardrail sections were inserted with the 3ds Max Civil View extension with dimensions taken from the Alaska Department of Transportation Standard Drawings Manual (AKDOT&PF, 2017). An example screenshot with centerline striping and guardrail is shown in Figure 3.10.



**Figure 3.10** Seward Highway with guardrail and field-matched striping

In addition to the three sections of highway, a short roadway section was designed to test the effects of guardrails on collision avoidance. The section consisted of a straight and level section of road for 2000 feet, followed by a 600-foot crest vertical curve ( $K = 205$ ). The section was marked with a double yellow centerline for its entirety. The tile was created with and without a guardrail at the curve. Screenshots of the collision avoidance portion of the experiment are shown in Figure 3.11.



**Figure 3.11** Screenshots of collision avoidance experiment (a) with guardrail and (b) without guardrail

### Simulated Traffic

Adjustments to the traffic were made based on preliminary results from the field data collection and results from the first stage. The speed of the same-lane traffic was increased to 57 mph based on field data. The posted speed limit was increased to 60 mph to encourage participants to pass and as a compromise between the actual posted speed limits of 55 mph for the Seward Highway and Sterling Highway and 65 mph for the Parks Highway. The speed of the oncoming vehicles was set at the posted speed limit. Since there were few unsafe pass attempts in the first stage, the density of the oncoming traffic was increased so that drivers had to accept shorter gaps. Vehicles were created at an average distance of one-quarter mile along each track; these distances were drawn from a normal distribution with a standard deviation of 300 feet. This variation was added to prevent participants from realizing that the traffic was regularly spaced and making passing decisions accordingly. The spacing between the same-lane vehicles was kept at one-quarter mile.

To test the effect of a guardrail on collision avoidance, an oncoming vehicle was programmed to be in the participant's travel lane overtaking another vehicle when the participant traveled over a crest vertical curve. The overtaking vehicle was programmed to travel at 65 mph and the overtaken vehicle was programmed to travel at 60 mph.

### Experimental Design

A standard Latin-square design for three track sections would have resulted in the Seward Highway section with no guardrail (section 1) preceding the Seward Highway section with guardrail (section 2) in 2 out of 3 conditions (see tracks 1–3 in Table 3.3). A counterbalancing Latin-square design in which the Seward Highway section with guardrail (section 2) preceded the Seward Highway section with no guardrail (section 1) in 2 out of 3 conditions (see tracks 4–6 in Table 3.3) was added to eliminate order effects.

At the end of the second drive (after all of the passing data were recorded), each participant encountered the collision avoidance portion of the experiment. A guardrail was present for half of the participants, and not present for the other half of the participants.

**Table 3.3** Latin square experimental design (Stage 2)

Track	Tile Order						
	Northbound			Break	Southbound		
Track 1	Seward (no GR)	Seward (GR)	Parks and Sterling		Parks and Sterling	Seward (GR)	Seward (no GR)
Track 2	Seward (GR)	Parks and Sterling	Seward (no GR)		Seward (no GR)	Parks and Sterling	Seward (GR)
Track 3	Parks and Sterling	Seward (no GR)	Seward (GR)		Seward (GR)	Seward (no GR)	Parks and Sterling
Track 4	Seward (GR)	Seward (no GR)	Parks and Sterling		Parks and Sterling	Seward (no GR)	Seward (GR)
Track 5	Seward (no GR)	Parks and Sterling	Seward (GR)		Seward (GR)	Parks and Sterling	Seward (no GR)
Track 6	Parks and Sterling	Seward (GR)	Seward (no GR)		Seward (no GR)	Seward (GR)	Parks and Sterling

### 3.3.3. Participant Recruitment

For each stage, participants with unrestricted valid driver licenses were tested. All of the participants were recruited from the community through advertising flyers posted in public places such as grocery shops, shopping centers, and on craigslist. Participants were required to be 18 years of age or older, and were paid \$20 per hour.

Participants recruited for the study were treated in accordance with the University of Idaho’s Institutional Review Board (IRB) protocol governing the use of human subjects in research. Before starting, participants were given a consent form to read, agree to, and sign. The consent form explained that a simulated virtual environment was going to be presented, and there was risk of simulator sickness associated with the study. The consent form stated that the participant’s task was to control the vehicle’s movement in the virtual world using input devices like a steering wheel, brake, and gas pedals. The form also stated that participation was going to require one session of approximately 60 minutes, that a participant could withdraw from the study at any time without penalty, and that the data collected would be kept anonymous.

A general description of the study was read to all drivers prior to participation. The description pointed out that the participants’ goal was to keep the vehicle centered in the lane and to travel at an appropriate speed, just as would occur in everyday driving. In the description, it was emphasized that participants would drive the vehicle as if they were in a hurry to get home from a long weekend trip. To avoid compromising the objective of the study, the instructions did not indicate that the participant had to pass other vehicles.

To ensure a firm understanding of the study procedures and familiarity with the control of the driving simulator, participants were given a 5- to 10-minute simulator test drive on a rural two-lane highway composed of straight and curved horizontal segments prior to actual testing. Participants were asked to enter the vehicle and adjust the rear-view mirror and driver’s seat to their preference. After completion of the test drive, participants were asked to remain seated while the experiment simulation was uploaded. The participants were again reminded that the steering wheel needed to be centered.

At the end of the experiment, a “Please pull over to the shoulder and stop” message was given to each participant, indicating that the experiment had ended. After making certain that the participant had pulled over and parked the vehicle, the researcher proceeded to stop the simulation. The researcher then stored and saved the experiment data in the appropriate folder for future analysis. Participants were asked to respond to a debriefing form provided by the researcher. Participants answered questions about their age, sex, and years of driving experience, whether they noticed anything unusual about the simulation, and what affected their driving behavior. Afterwards, the participants were informed of the study’s purpose, and the researcher answered any questions that the participants had about the study. The participant was subsequently compensated for his or her time.

#### *3.3.4. Experimental Procedure*

Basic instructions were read to all drivers prior to participation. The instructions stated that the driver’s goal was to keep the vehicle centered in the lane and to travel at an appropriate speed, just as in everyday driving. To induce a sense of urgency and increase the number of passing maneuvers, the participants were instructed to drive as if in a hurry. In the first stage, the instructions state that the participant is in a hurry “to get home from a weekend long trip.” In the second stage, the instructions state that the participant is in a hurry “for a family emergency.” This heightened urgency was deemed necessary to encourage participants to pass vehicles at higher speeds than in the previous stage.

The participants then completed a short test drive in the simulator to become familiar with the controls of the vehicle. Each participant drove the sequence of tracks indicated in the experiment design, with a short break between the two scenarios. After the completion of both test scenarios, the participants completed a brief questionnaire regarding the simulation, their driving history, and selected personal demographics.

#### *3.3.5. Data Reduction*

Each session recorded about 1 gigabyte of data that was stored in a data acquisition (.daq) format. These data contained microscopic information related to vehicle dynamics, user input, and position. Data related to vehicle dynamics included speed and acceleration. User input data included steering wheel angle, accelerator position, brake pedal position, turn signal position, and gear selector position. Position data included the vehicle’s coordinates, lane position, and following distance, as well as the coordinates of every vehicle in the scenario. All .daq files were converted into a hierarchical data format (hdf5) for data reduction.

A script was written using an IPython interface to identify when passes were attempted. Several variables related to each pass attempt were either recorded directly from the raw data or calculated, including the location of the participant’s vehicle at initiation and conclusion of the maneuver; distance to the impeding vehicle and oncoming vehicle at initiation and conclusion of the maneuver; the total time and distance spent in the opposing lane; the vehicle’s speed when abreast of the impeding vehicle; and the time to contact to the oncoming vehicle at initiation and conclusion of the maneuver. The location of the vehicle at the time of initiation was then used to extract data such as sight distance, slope, and horizontal and vertical curvature.

A script was also written to extract frames from each drive to build a dataset that included the pass attempts from the pass counting script as well as frames at which the drivers chose not to

pass. The script looped through each drive and sampled frames from a uniform distribution of 10–30 seconds. If a pass attempt occurred within the next 20 seconds, the script would record geometric and situational variables for the frame at which the pass attempt was initiated and record “attempt” for the outcome variable. If no attempt occurred, the variables were recorded for the frame that was sampled, and “none” was recorded for the outcome variable. The frames were only sampled if the driver was within 250 feet of an impeding vehicle so that a pass attempt was possible; of the observed pass attempts, this distance represented the 98<sup>th</sup> percentile of the following-distance distribution.

Finally, a script was written to extract information regarding how participants in the second stage reacted to the vehicle in their lane. Specifically, the script recorded whether the driver collided with the oncoming vehicle and how far the driver moved toward the edge of the road (lane deviation).

## CHAPTER 4. RESULTS AND ANALYSIS

### 4.1. Field Data

The extracted rates of observed passing maneuvers from the video observations are shown in Figure 4.1 and a corresponding summary of their characteristics in Table 4.1. Note that averages are not given for passing maneuver types with less than three observations. Vehicle positions during passing maneuvers on segments of the Parks (Observation Period 1 and 2), Seward, and Sterling highways can be seen in Figure 4.2 through Figure 4.5, respectively.



**Figure 4.1** Observed passing maneuver type by field site location

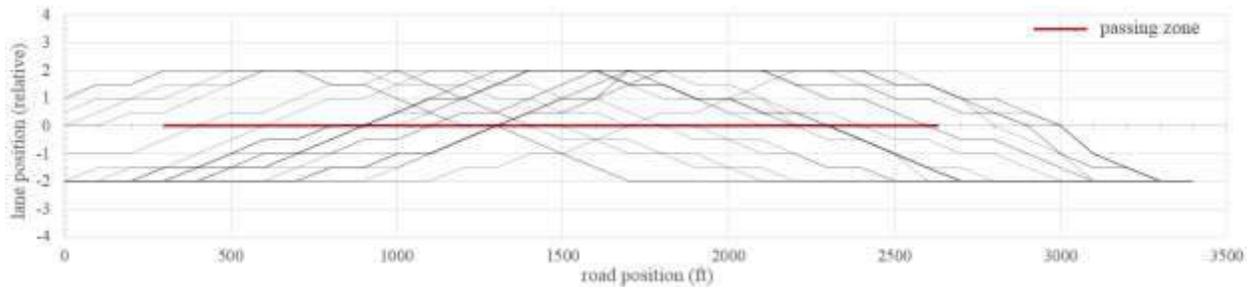
**Table 4.1** Real-world passing maneuver summary statistics

	Parks Highway (1)	Parks Highway (2)	Seward Highway	Sterling Highway
Passing Maneuvers Observed	23	11	18	7
Passing Maneuver Characteristics (mph)				
<i>All Observations</i>				
Average Max Vehicle Speed – Passing	74.3	72.1	65.2	65.3
SD of Max Vehicle Speed – Passing	6.9	7.3	4.9	3.9
Average Initial Speed – Passing	69.2	70.1	58.1	57.3
Average Final Speed – Passing	77.2	78.4	64.9	66.2
Average Initial Speed – Passed	67.4	66.2	56.4	56.7
SD of Initial Vehicle Speed – Passed	5.5	4.4	3.5	3.2
Passing Maneuver Characteristics (mph)				
<i>Early Initiated Passes</i>				
Average Max Vehicle Speed – Passing	77.4	+	--	67.2
SD of Max Vehicle Speed – Passing	3.1	+	--	3.2
Average Initial Speed – Passing	71.1	+	--	59.7
Average Final Speed – Passing	77.2	+	--	66.9
Average Initial Speed – Passed	67.5	+	--	55.8
SD of Initial Vehicle Speed – Passed	2.8	+	--	2.7

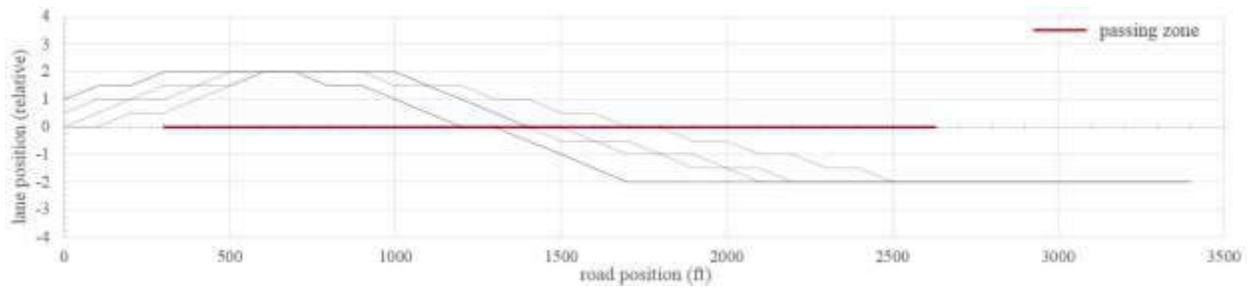
	Parks Highway (1)	Parks Highway (2)	Seward Highway	Sterling Highway
Passing Maneuvers Observed	23	11	18	7
Passing Maneuver Characteristics (mph)				
<i>Late-finish Passes</i>				
Average Max Vehicle Speed – Passing	76.2	--	67.7	--
SD of Max Vehicle Speed – Passing	4.7	--	3.8	--
Average Initial Speed – Passing	67.3	--	59.2	--
Average Final Speed – Passing	76.3	--	64.5	--
Average Initial Speed – Passed	65.1	--	58.4	--
SD of Initial Vehicle Speed – Passed	3.3	--	2.9	--

The Parks Highway segment had the highest percentage of early-start passing maneuvers, while the Seward Highway had the highest percentage of late-finish passes. Average speeds of the passing and passed vehicles tended to be much higher than the average speeds assumed in the AASHTO standards. The difference in speeds between the passing vehicle (taken as the max speed reached during the passing maneuver) and the vehicle being passed (speed at the initiation of the passing event) varied depending on the type of passing maneuver. For early-start passes, the difference was about 7.5 mph on average. For late-finish passes, the difference was closer to 9 mph. For compliant-type passes, the difference varied by location, as low as 6 mph average for the Parks Highway and 9 mph average for the Sterling and Seward highways. The standard deviation of speeds for compliant passes was larger than that of late- and early-type passes.

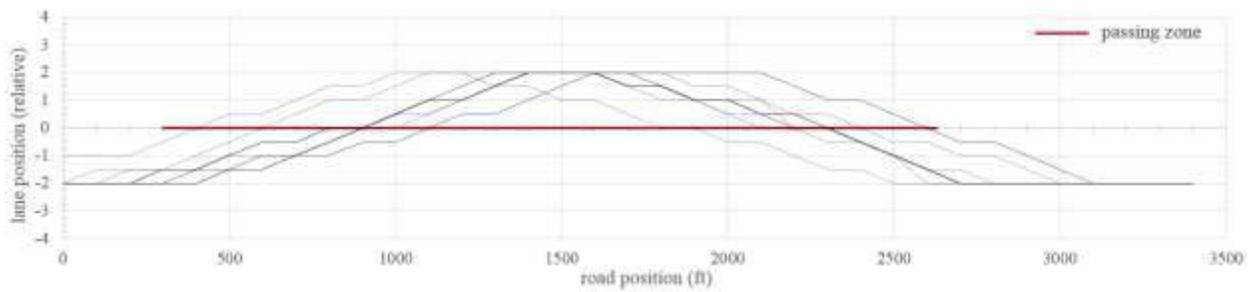
In general, drivers who executed compliant-type passing maneuvers tended to occupy the opposing lane for less time ( $\bar{x} = 1268$  feet) than those who executed late- and early-type passing maneuvers ( $\bar{x} = 1413$  feet and  $\bar{x} = 1382$  feet, respectively). However, only the late and compliant passing maneuvers exhibited a statistically significant difference ( $p = 0.0474$ ) when comparing across all sites (see Figure 4.6). When comparing within sites, this difference between late- and compliant-type passing maneuvers was not exhibited at the Seward Highway section.



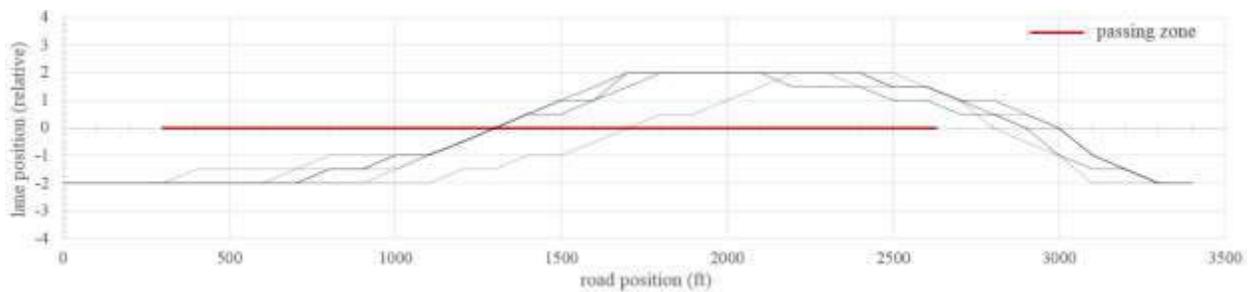
(a)



(b)

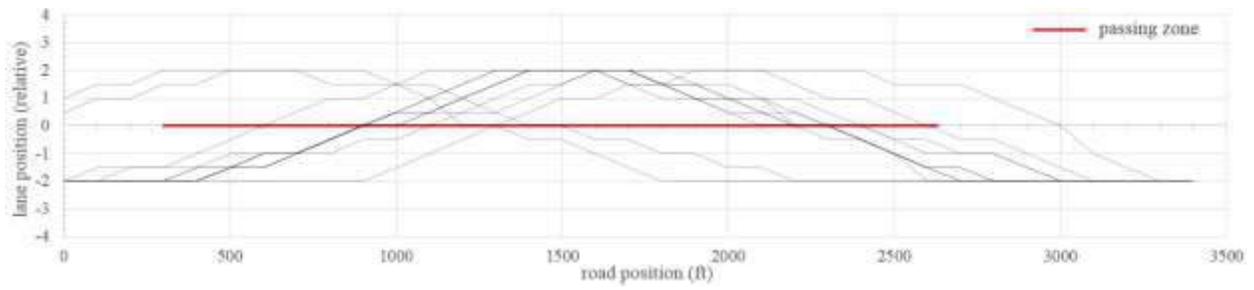


(c)

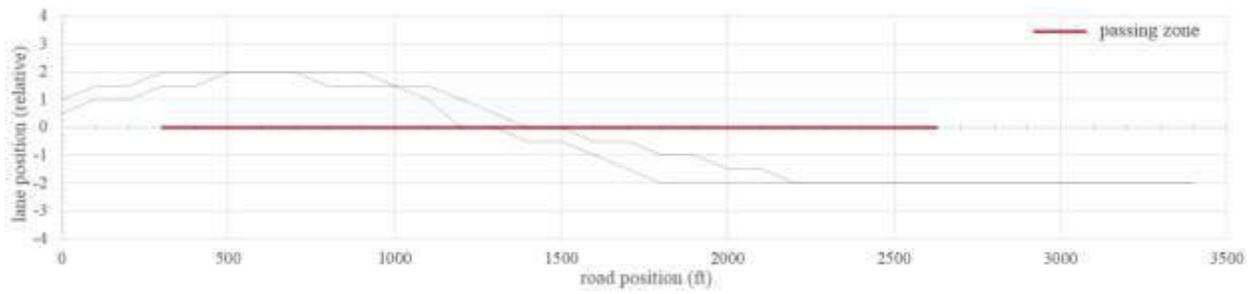


(d)

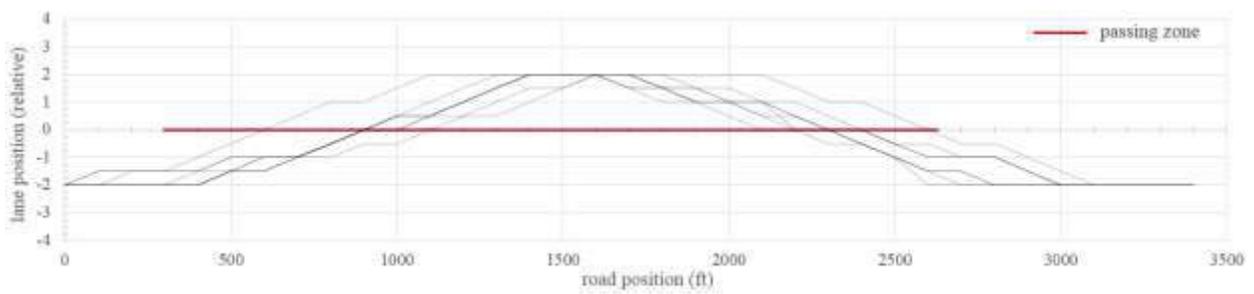
**Figure 4.2** Vehicle position during (a) all, (b) early-start, (c) compliant, and (d) late-finish passing maneuvers on Parks Highway segment (Observation Period 1)



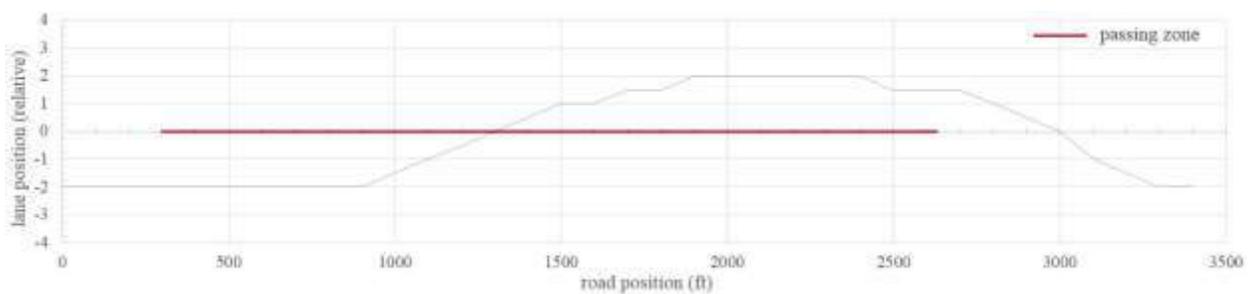
(a)



(b)

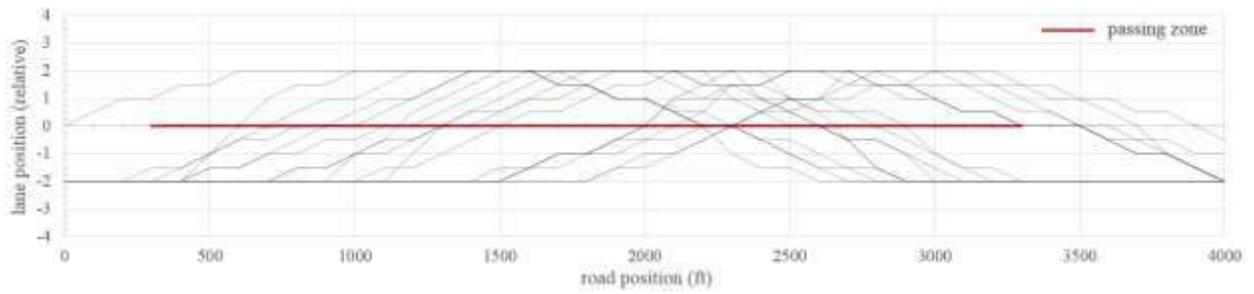


(c)

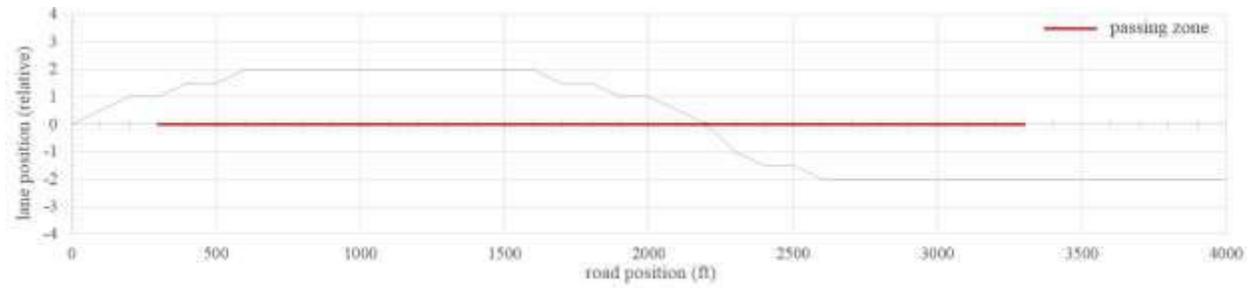


(d)

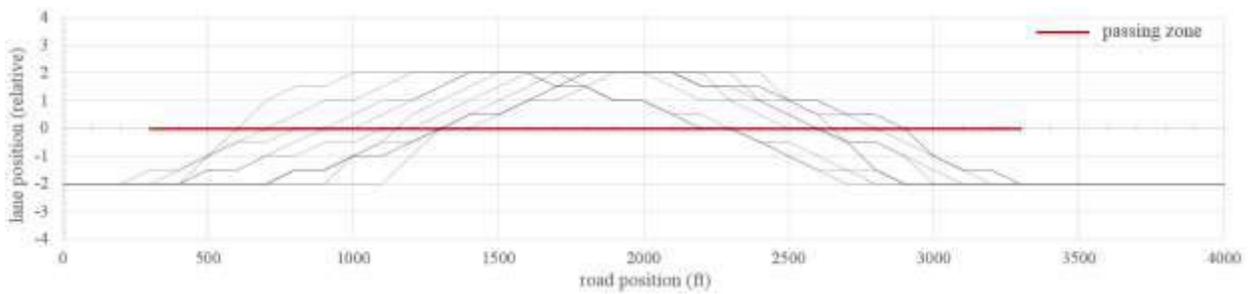
**Figure 4.3** Vehicle position during (a) all, (b) early-start, (c) compliant, and (d) late-finish passing maneuvers on Parks Highway segment (Observation Period 2)



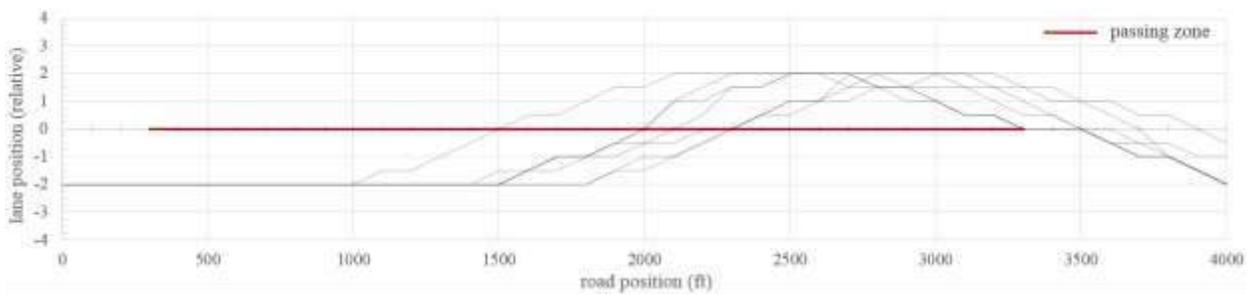
(a)



(b)

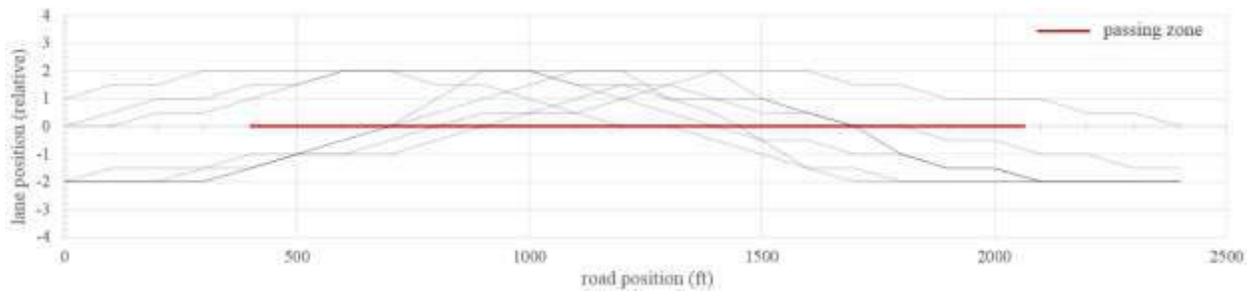


(c)

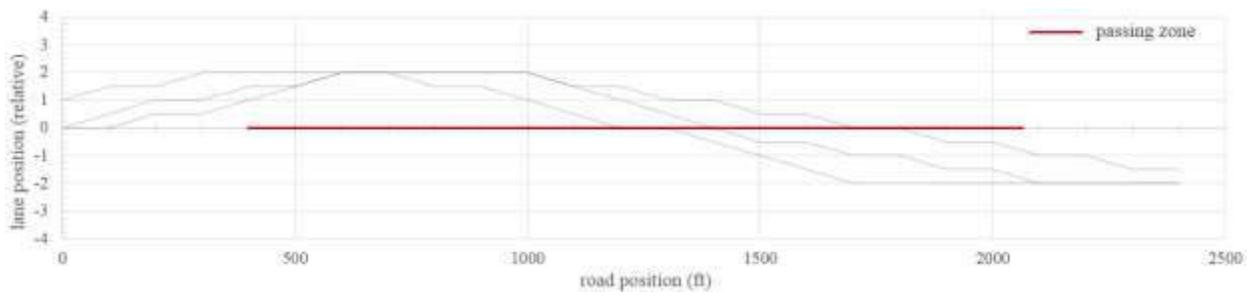


(d)

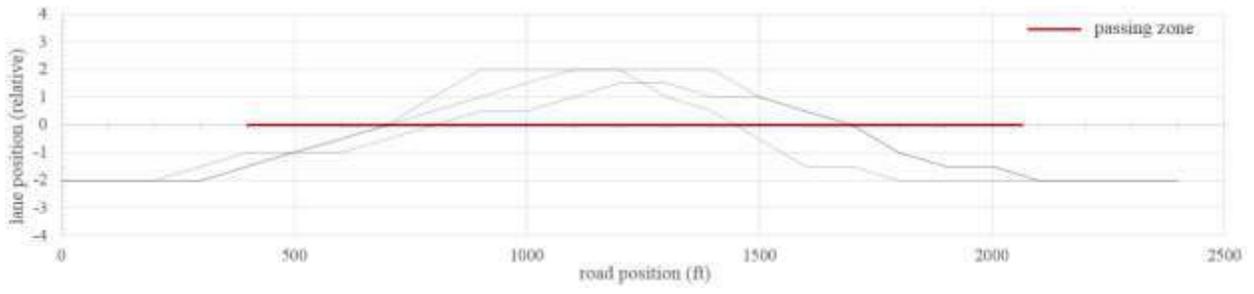
**Figure 4.4** Vehicle position during (a) all, (b) early-start, (c) compliant, and (d) late-finish passing maneuvers on Seward Highway segment



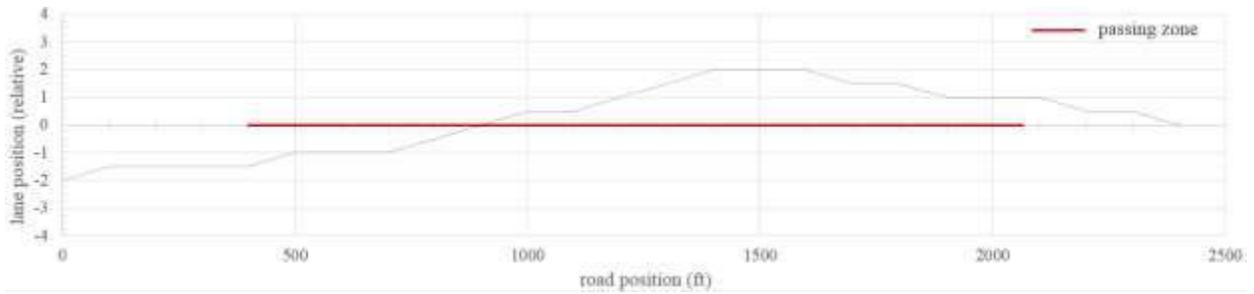
(a)



(b)

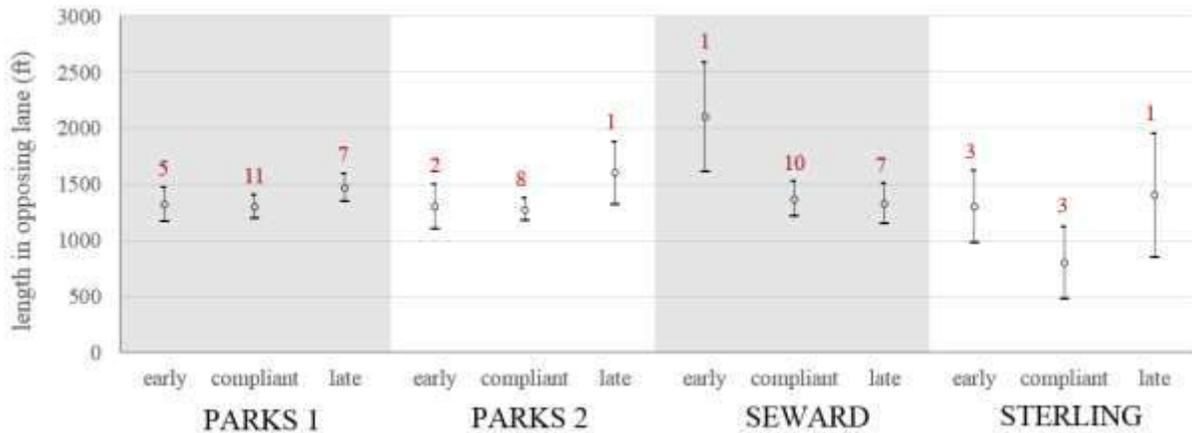


(c)



(d)

**Figure 4.5** Vehicle position during (a) all, (b) early-start, (c) compliant, and (d) late-finish passing maneuvers on Sterling Highway segment



**Figure 4.6** Site comparisons of distance spent in opposing lane while executing passing maneuver by execution type (early, compliant, and late)

## 4.2. Driving Simulator

The following sections provide a comparison of the passing locations under dashed centerline (first stage) and field-matched centerline (second stage) conditions. First stage results, including a logistic model of driver passing choice, characterization of passing maneuvers, and analysis of passing safety under different geometric conditions are then presented, followed by a discussion of the causal effects of a guardrail on passing behavior and collision avoidance.

### 4.2.1. Participant Information

Seventy-two participants were recruited to complete simulation testing for both stages. Table 4.2 is a summary of participants' demographics.

**Table 4.2** Driving simulator participants' demographics

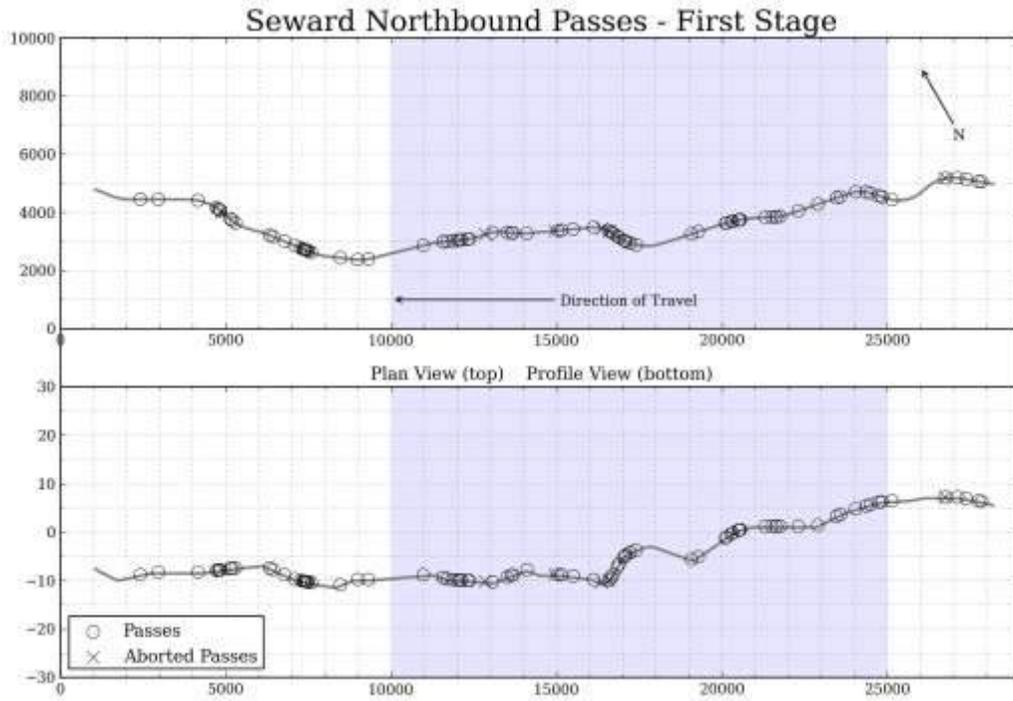
	1 <sup>st</sup> Stage	2 <sup>nd</sup> Stage
<b>Age</b>		
Minimum	18	18
Maximum	60	78
Mean	27.5	28.6
<b>Driving Experience</b>		
Minimum	3	2
Maximum	45	60
Mean	11.5	13.2
<b>Sex</b>		
Male	16	27
Female	8	21
<b>Marital Status</b>		
Single	19	34
Married	5	14

### 4.3. Passing Locations

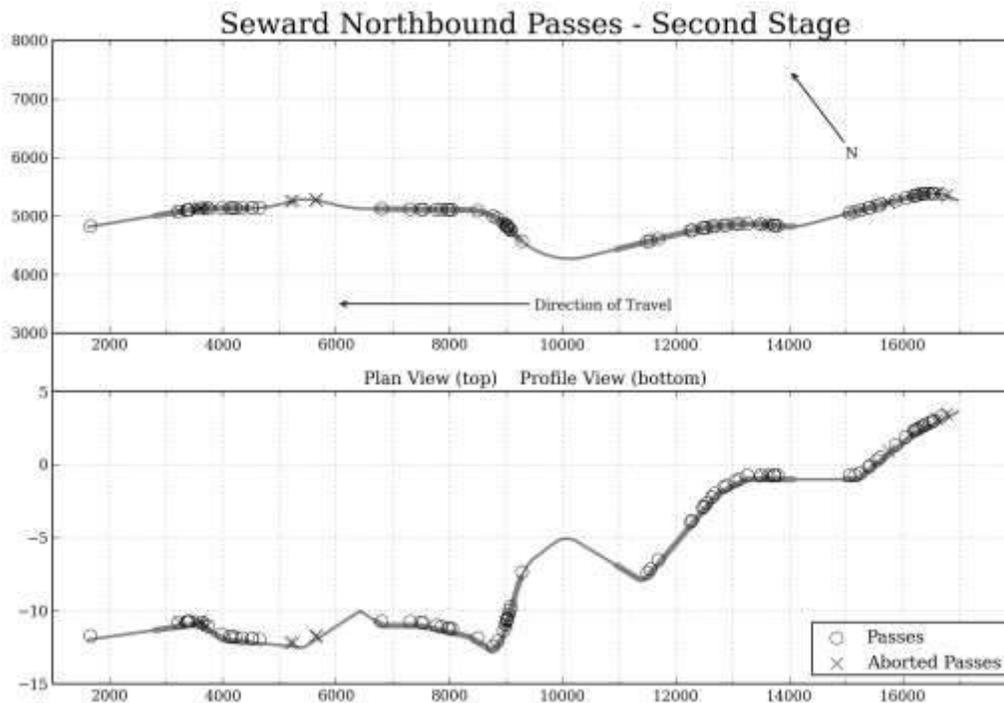
To examine passing behavior along the existing roadway alignment, centerline roadway geometry provided by the AKDOT&PF was utilized and incorporated into the driving simulator data files. Although the study design was limited by the constraints of the driving simulator parameters (i.e., static speeds for vehicles being passed and of the oncoming vehicles), this research sought to pinpoint the specific locations along the roadway alignment where passes occurred. Each participant encountered a dashed yellow centerline stripe for the first stage of the experiment so that a pass could be initiated at any location where the driver felt comfortable doing so. The participants encountered striping as it occurs on the actual roadway alignment for the second stage of the experiment to examine the effects of striping on passing location.

The initiation location of each completed and aborted passing maneuver was plotted on plan-view and profile-view plots of each highway section, the results of which are shown in Figure 4.7 to Figure 4.12. Part (a) of each figure shows the pass attempts in the first stage (unrestricted passing), and part (b) of each figure shows the pass attempts in the second stage. The gray-highlighted portion of the first stage plots corresponds to the shortened sections tested in the second stage. The passing zones in the second stage are indicated by wider centerlines in the plots. Each figure identifies the horizontal curvature (shown in the top section in the plan view) and the accompanying vertical curvature (shown in the bottom section in the profile view) for both the northbound and southbound directions. The coordinates indicated in each figure correspond to how the road alignment was positioned in the simulator files and are arbitrary in terms of real-world position; however, the scale is correct and units are in feet.

On the Parks Highway and Sterling Highway test sections, there is no clear relationship between horizontal curvature and pass attempt locations, though the attempts appear to cluster downstream from crest vertical curves. In contrast, the pass attempts appear to cluster downstream from horizontal curves along the Seward Highway test section, as the vertical curvature on this section is minimal. These patterns are consistent with the expectation that drivers are less likely to pass when sight distance is restricted. Sight distance is primarily restricted by crest curves on the Parks Highway and Sterling Highway test sections, and is primarily restricted by the horizontal curves on the Seward Highway test section.

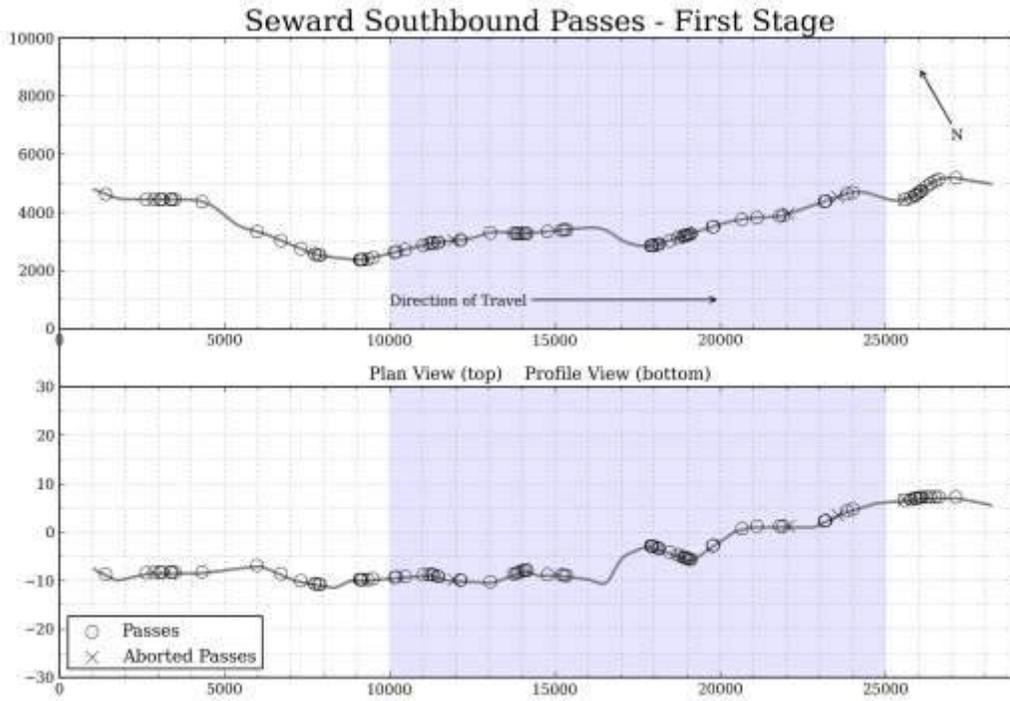


(a)

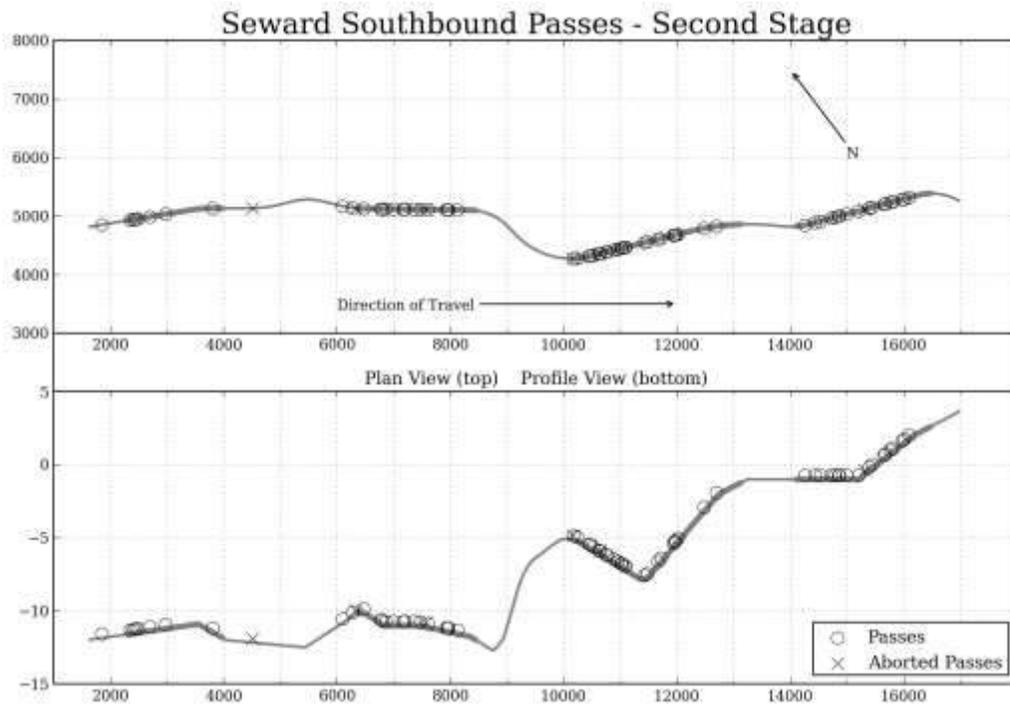


(b)

**Figure 4.7** Driver passing locations on Seward Highway (NB) during (a) first stage and (b) second stage

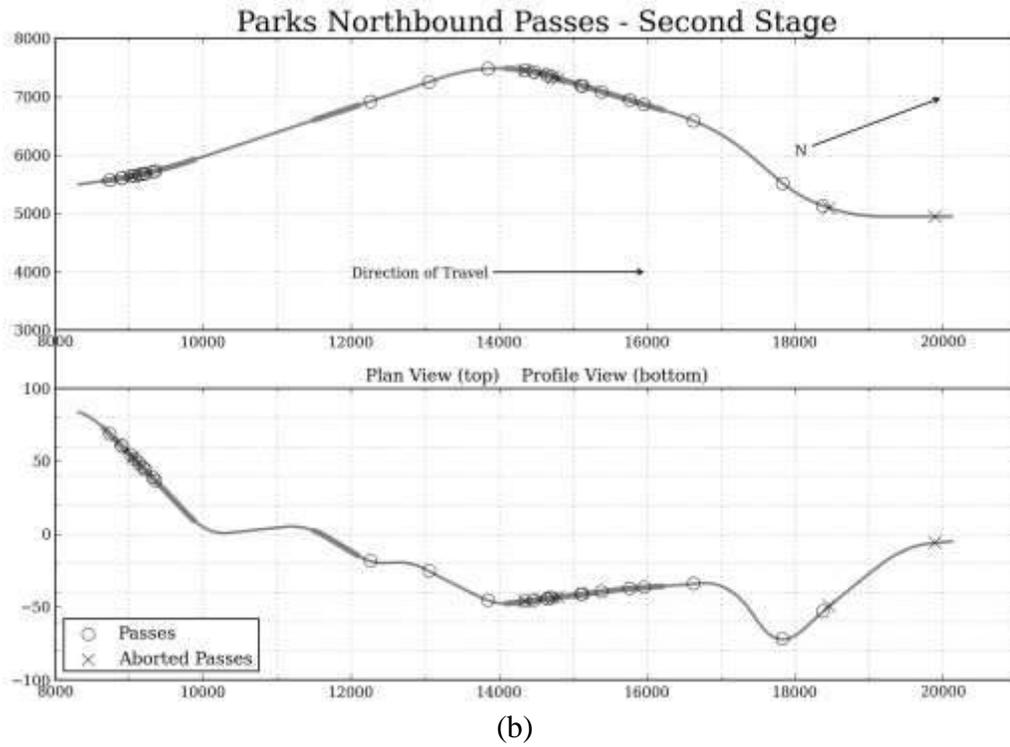
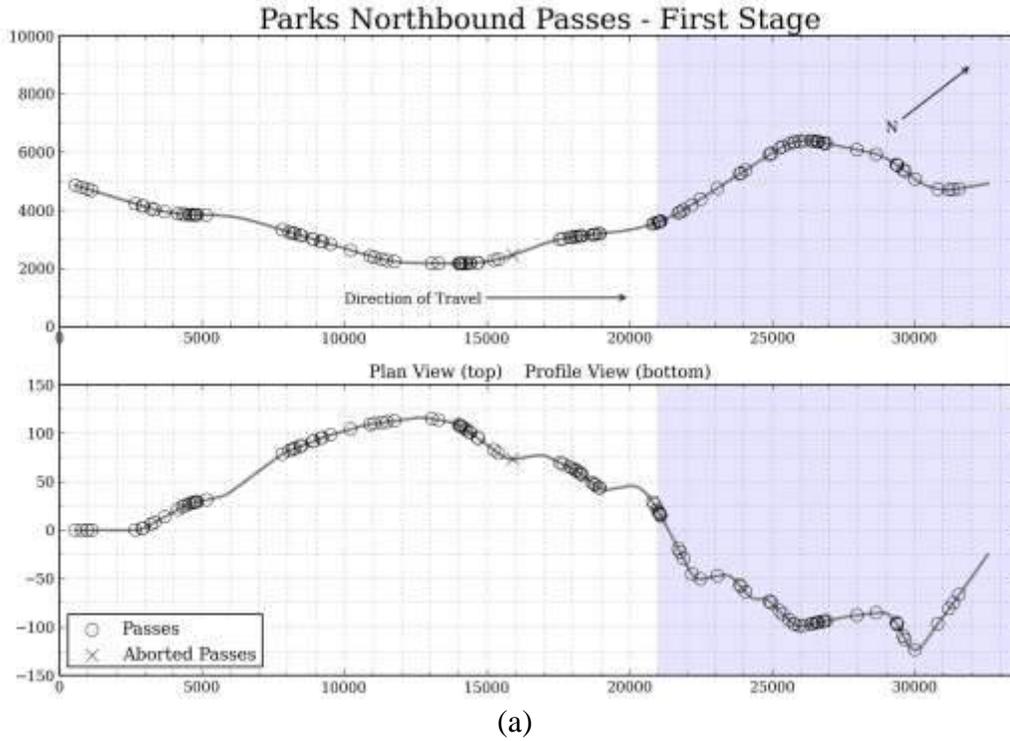


(a)

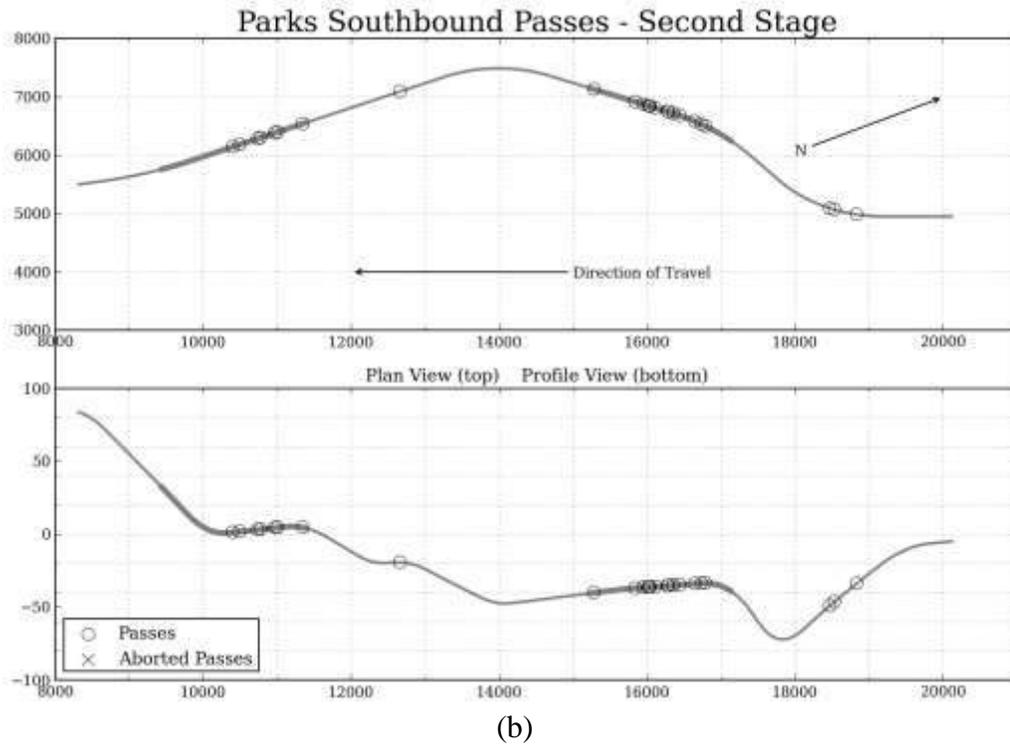
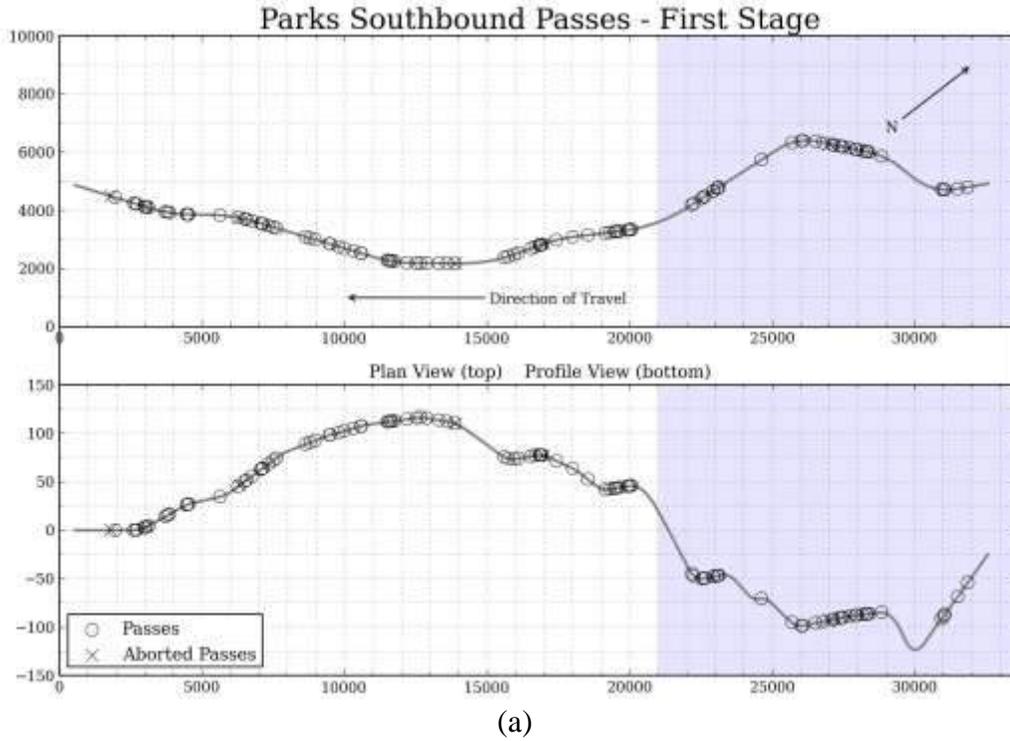


(b)

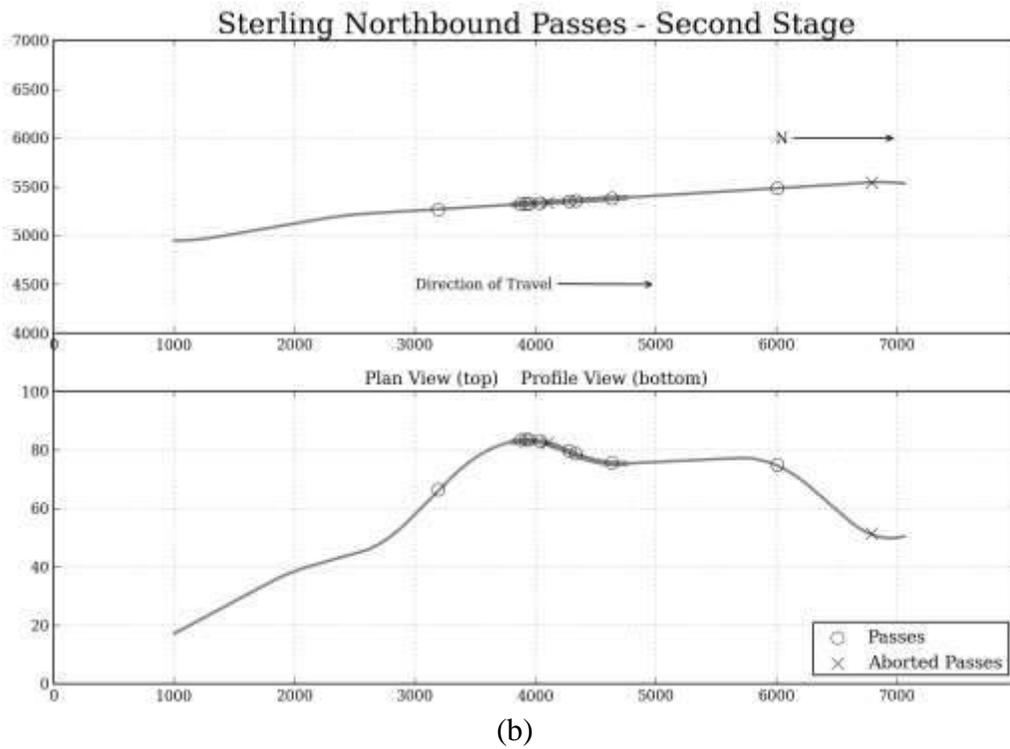
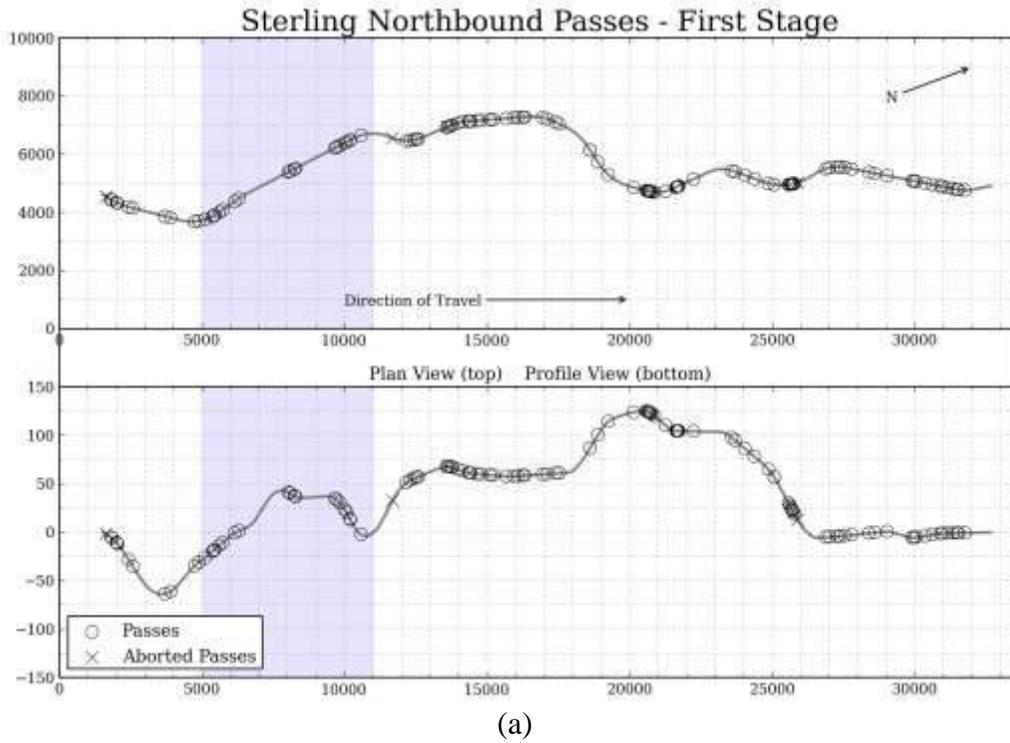
**Figure 4.8** Driver passing locations on Seward Highway (SB) during (a) first stage and (b) second stage



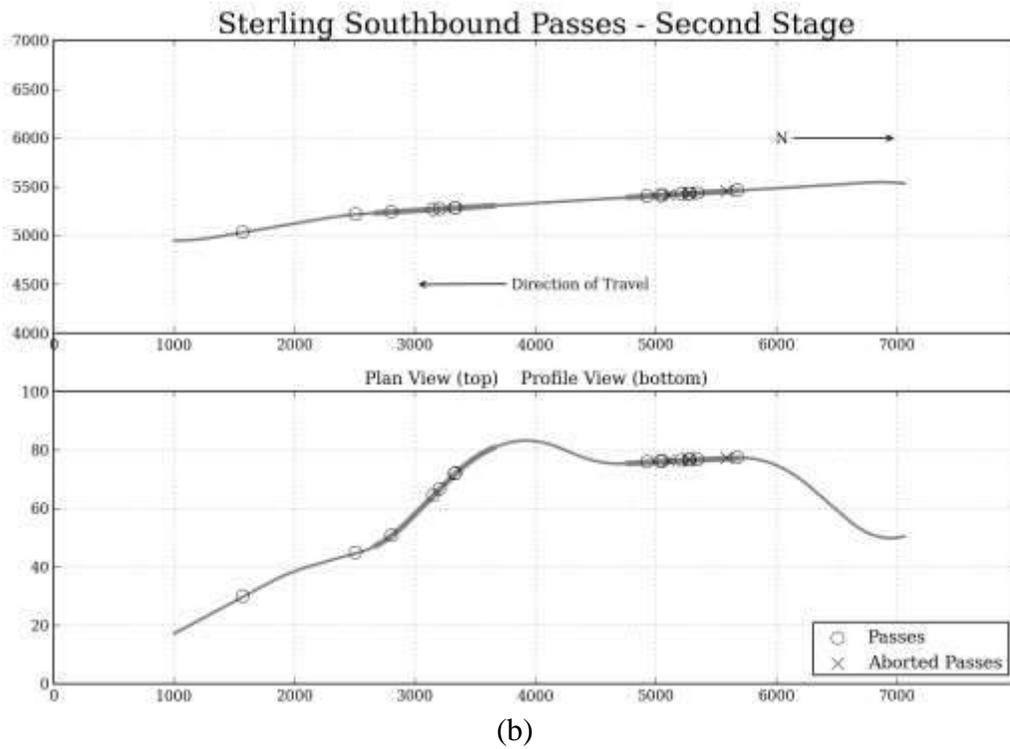
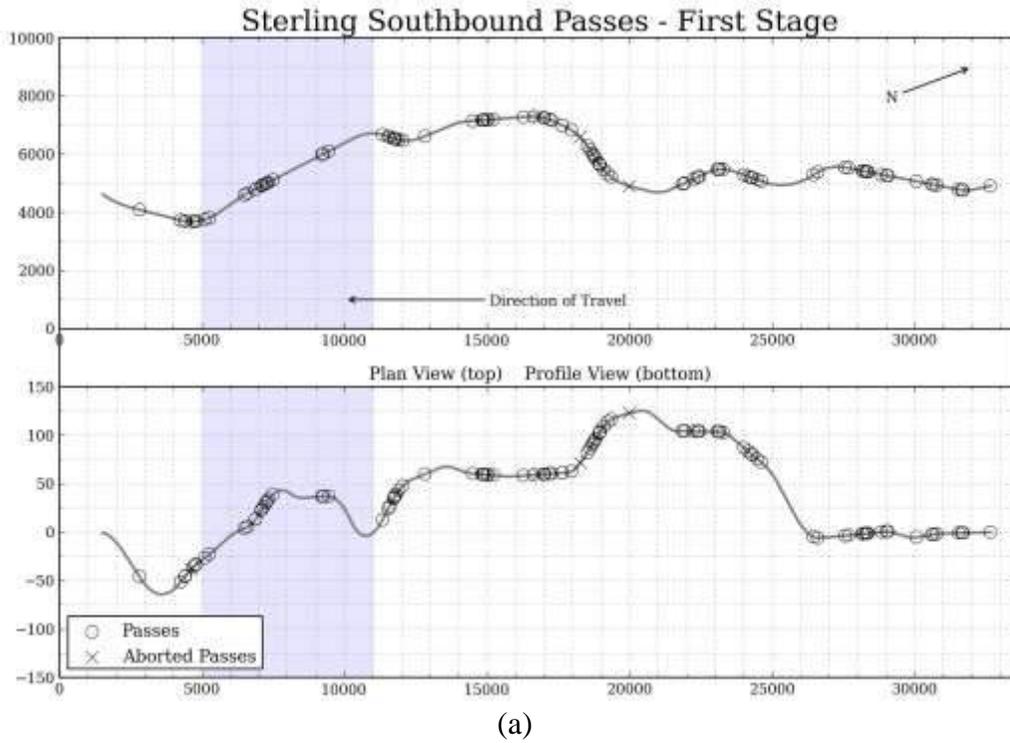
**Figure 4.9** Driver passing locations on Parks Highway (NB) during (a) first stage and (b) second stage



**Figure 4.10** Driver passing locations on Parks Highway (SB) during (a) first stage and (b) second stage



**Figure 4.11** Driver passing locations on Sterling Highway (NB) during (a) first stage and (b) second stage



**Figure 4.12** Driver passing locations on Sterling Highway (SB) during (a) first stage and (b) second stage

## 4.4. Data Analysis – First Stage

### 4.4.1. Passing Choice Logistic Model

A mixed-effects logistic regression model was developed to infer the effects of geometric configuration on the choice to pass. Situational variables and driver characteristics variables were included in the model to control for variability. The geometric variables included the slope, horizontal curvature, and vertical curvature, which were recorded as the change in curvature (heading in degrees and slope in percent) in the previous and subsequent 500-foot and 1000-foot segments of road. The 1000-foot length was chosen because 1000 feet was the approximate average distance that a passing maneuver took to complete, and the 500-foot distance was chosen to quantify how much of the curvature occurred in the early or late portions of the maneuver. Situational variables included the following distance (i.e., distance to impeding vehicle), distance to sight obstruction, and whether the sight obstruction was a natural sight obstruction or an oncoming vehicle. Driver characteristics variables included demographic variables and average speed. Participant identification (PID) was included in the model as a random effect. The variables that were considered for the model are summarized in Table 4.3. The distance to sight obstruction variable was transformed by taking the square root, which resulted in an improved model fit.

**Table 4.3** Description of variables considered for passing choice logistic model

Variable	Description
event (dependent variable)	1 = pass attempted; 0 = otherwise
Sterling	1 = Sterling; 0 = otherwise
Seward	1 = Seward; 0 = otherwise
right500, left500	change in heading in 500 feet of road from driver's location [degrees]; if < 0 absolute value was taken and this was <i>left</i> variable, if > 0 then <i>right</i> variable; 0 = if road was straight or curved in opposite direction
right1000, left1000	change in heading in 1000 feet of road from driver's location [degrees]; if < 0 absolute value was taken and this was <i>left</i> variable, if > 0 then <i>right</i> variable; 0 = if road was straight or curved in opposite direction
sag500, crest500	change in slope in 500 feet of road from driver's location; if < 0 absolute value was taken and this was <i>crest</i> variable, if > 0 then <i>sag</i> variable; 0 = if road was flat or curved in opposite direction
sag1000, crest1000	change in slope in 1000 feet of road from driver's location; if < 0 absolute value was taken and this was <i>crest</i> variable, if > 0 then <i>sag</i> variable; 0 = if road was flat or curved in opposite direction
up, down	slope at driver's location; if < 0 absolute value was taken and this was <i>down</i> variable, if > 0 then <i>up</i> variable; 0 = if road was level or sloped in opposite direction
b_right500, b_left500	change in heading in 500 feet of road previous to driver's location [degrees]

**Table 4.3 (cont.)** Description of variables considered for passing choice logistic model

Variable	Description
b_right1000, b_left1000	change in heading in 1000 feet of road previous to driver's location [degrees]
b_sag500, b_crest500	change in slope in 500 feet of road previous to driver's location
b_sag1000, b_crest1000	change in slope in 1000 feet of road previous to driver's location
obdist	distance from driver to sight distance obstruction (either natural obstruction or oncoming vehicle) [feet]; defined as minimum between distance to oncoming vehicle ( <i>dist</i> ) and sight distance ( <i>SD</i> )
obtype	type of sight distance obstruction: 1 = oncoming vehicle ( <i>dist</i> < <i>SD</i> ); 0 = natural sight distance obstruction ( <i>SD</i> < <i>dist</i> )
avg_speed	driver average speed while traveling in own lane unimpeded
sex	1 = male; 0 = female
mar_stat	1 = married; 0 = single

The final model was chosen based on backwards elimination by removing the variables with the highest probability of not meeting the chosen significance criterion ( $p < 0.10$ ). The 500-foot and 1000-foot segment alternatives of the horizontal and vertical curvature variables were compared, and the more significant alternative was chosen to remain in the model. The 500-foot alternatives were more significant for the horizontal curvature variables and the previous sag curvature, while the 1000-foot alternatives were more influential for the vertical curvature. The final model is summarized in Table 4.4.

**Table 4.4** Summary of final logistic model

Variable	Scaled Coefficient	Standard Error	z-value
Intercept	-0.729	0.205	-3.558 ***
Seward	-0.987	0.187	-5.274 ***
up	-0.390	0.086	-4.524 ***
right500	-0.182	0.088	-2.065 *
left500	0.170	0.076	2.229 *
crest1000	-0.781	0.139	-5.626 ***
sag1000	0.188	0.092	2.047 *
b_sag500	-0.249	0.083	-3.004 **
follow	-0.679	0.098	-6.925 ***
sqrt(obdist)	1.293	0.099	13.020 ***
obtype	-0.531	0.168	-3.162 **
avg_speed	1.156	0.176	6.566 ***
age	-0.509	0.183	-2.776 **
<i>Random effects:</i>	<i>(Intercept / PID) Variance = 0.627, Standard Deviation = 0.792</i>		
<i>Model fit:</i>	<i>Null LL = -907.7, Final LL = -606.6, McFadden's R<sup>2</sup> = 0.332</i>		
<i>Significance:</i>	<i>* = (p &lt; 0.05) ** = (p &lt; 0.01) *** = (p &lt; 0.001)</i>		

The model showed significant effects for the highway section, slope, horizontal curvature, vertical curvature, following distance, distance to sight obstruction, and type of sight obstruction, as well as the age and average speed of the driver. Drivers were less likely to pass on the Seward Highway section than on the Parks Highway or Sterling Highway sections. The reason for this is unclear, although there are several possible contributing factors. First, it is possible that the highway section variable interacts with some of the other geometric variables in complex ways that are not described by this model. Other iterations of the model showed weak interactions between the section variables and geometric variables that were discarded because the effects were not shown to be statistically significant, although the cumulative effect of these interactions may be significant. Additionally, 41.7% of participants reported that the cliff decreased their likelihood to choose to pass, some due to the sight distance restriction and others due to discomfort with driving between a cliff and a body of water.

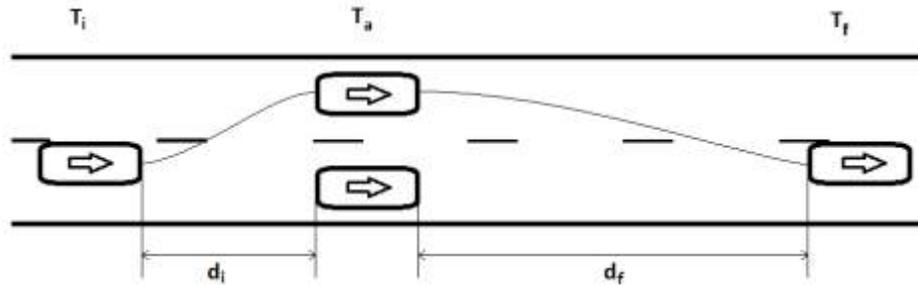
Drivers were less likely to pass when the road turned to the right in the next 500 feet than if the road was straight, and they were more likely to pass if the road turned left than if the road was straight. Two factors likely contribute to a preference for passing on left-hand curves; first, passing on a left-hand curve flattens the overtaking vehicle's path and shortens the path length through the curve, and second, the impeding vehicle often obstructs the sight distance for the overtaking driver on straight sections and right-hand curves.

Drivers were less likely to pass when there was a crest curve within the next 1000 feet than if the road was flat, and they were more likely to pass if the road had a sag curve within the next 1000 feet than if the road was flat. Drivers were less likely to pass if there was a sag curve within the previous 500 feet than if the road was flat. Finally, drivers were less likely to pass when they were traveling uphill than if they were traveling on level road or downhill.

Of course, drivers were also more likely to pass as the distance to the sight obstruction increased, and were less likely to pass if the sight obstruction was a vehicle than if it was a natural sight restriction. Drivers were more likely to pass as the follow distance decreased, which makes sense because drivers close the gap when they are preparing to pass. Finally, drivers were more likely to pass if their average speed was higher and less likely to pass as their age increased.

#### *4.4.2. Passing Maneuver Characterization by Geometric Configuration*

The vehicle speed when abreast of the impeding vehicle, total time spent in the opposing lane, total distance traveled in the opposing lane, following distance at the initiation of the pass, and distance from the impeding vehicle at the end of the maneuver were calculated for each passing maneuver (see Figure 4.13).  $T_i$  is the time when the vehicle breaches the centerline,  $T_a$  is the time when the vehicle is abreast of the impeding vehicle, and  $T_f$  is the time when the vehicle returns fully to its own lane. Speed abreast is the speed at  $T_a$ , total time spent in opposing lane is the time in seconds between  $T_i$  and  $T_f$ , the distance traveled is the distance traveled between times  $T_i$  and  $T_f$ , following distance at the initiation is  $d_i$ , and distance from the impeding vehicle at the end of the maneuver is represented by  $d_f$ .



**Figure 4.13** Passing maneuver characteristics

The data were subdivided into geometric configurations based on the change in heading (left, right, and straight) and slope (sag, crest, and flat) in the 500-foot and 1000-foot segments of road following the initiation of each pass. Pairwise comparisons of the means of each variable for each geometric configuration were performed using a *t*-test at the 95% confidence level. The results are summarized in Table 4.5 and Table 4.6; significant differences are denoted as indicated in the footnotes of each table. For example, the mean speed when the road was straight for at least 500 feet from pass initiation, 64.9 mph, is statistically significantly greater than the mean speed when the road curved to the right within 500 feet from pass initiation, 63.5 mph, which is indicated by an asterisk (\*). Likewise, the mean speed when the road was straight for at least 1000 feet from pass initiation, 65.4 mph, is statistically significantly greater than the mean speed when the road curved to the left within 1000 feet from pass initiation, 63.8 mph, which is indicated by a cross (†).

Horizontal curvature affected every measure that was compared. During passing maneuvers, drivers tended to reach higher speeds when passing on straight sections of road than on curves. These differences were small (less than 2 mph, on average), so little practical significance was gained. Vehicles were in the oncoming lane for shorter times and distances on average when the road curved to the right than when the road was straight or curved to the left. This difference corresponds to a substantial reduction in distance between the vehicle and the passed vehicle when the pass was finished and the vehicle returned to its own lane, which averaged 176.7 feet on left curves, 188.8 feet on straight sections, and 148.2 feet on right curves. Similarly, when the roadway curved to the right within 500 feet of initiation of the pass, the average following distance at the initiation of the pass was 101.7 feet compared with 115.4 feet when the road was straight.

When the road had a sag curve within 500 feet of the pass initiation, the average speed of the vehicle while abreast of the impeding vehicle was 65.8 mph compared with 63.6 mph when the road was flat or had a crest curve. The higher speed on sag curves corresponds to less time spent and distance traveled in the opposing lane. Each of these differences only occurred when the sag curve was in the early portion (less than 500 feet from initiation) of the passing maneuver and diminished if the sag curve was within 1000 feet of the initiation of the maneuver.

**Table 4.5** Passing maneuver characteristics on horizontal curves

	500 ft			1000 ft		
	Left N=218	Straight N=256	Right N=143	Left N=289	Straight N=151	Right N=177
Vehicle Speed (when abreast, in mph)	64.0	64.9*	63.5	63.8	65.4†	64.0
Total Time Spent (opposing lane, in seconds)	11.4*	11.1	10.6	11.4*	11.3*	10.4
Total Distance Traveled (opposing lane, in feet)	1035.2*	1024.1*	957.6	1036.5*	1049.8*	941.9
Finish Distance (to impeding vehicle, in feet)	174.2*	178.7*	152.8	176.7	188.8	148.2
Initial Follow Distance (to impeding vehicle, in feet)	112.0	115.4*	101.7	110.5	117.1	106.6

Significant ( $p < 0.05$ ) differences indicated by: \* > Right, † > Left

**Table 4.6** Passing maneuver characteristics on horizontal curves

	500 ft			1000 ft		
	Crest N=158	Flat N=286	Sag N=173	Crest N=179	Flat N=161	Sag N=277
Vehicle Speed (when abreast, in mph)	63.6	63.6	65.8*†	64.3	63.5	64.7
Total Time Spent (opposing lane, in seconds)	11.5‡	11.3‡	10.4	11.2	11.4	10.9
Total Distance Traveled (opposing lane, in feet)	1037.8‡	1024.0‡	970.8	1013.6	1035.0	999.0
Initial Follow Distance (to impeding vehicle, in feet)	109.6	108.3	116.7	110.0	106.6	114.2
Finish Distance (to impeding vehicle, in feet)	170.8	173.3	169.1	168.2	178.7	169.4

Significant ( $p < 0.05$ ) differences indicated by: \* > Flat, † > Crest, ‡ > Sag

#### 4.4.3. Passing Safety by Geometric Configuration

The most important variable regarding passing safety is the final time to contact (TTC), which is the most direct measure of how close a driver executing a passing maneuver comes to colliding with a vehicle in the oncoming lane. A common criterion used to determine whether a pass is excessively risky is if the final TTC is less than 3 seconds (Farah, et al., 2009). The proportion of passes that ended in an unsafe time to contact was calculated for each section. The most important factor influencing the outcome of a passing maneuver is the distance to the oncoming vehicle when the driver chooses to initiate the pass.

To compare passing safety in this experiment, the average final TTC, proportion of unsafe passes, and average initial distance to an oncoming vehicle were recorded for each pass, and a pairwise comparison was performed by geometric configuration. A subset of the data for which

the initial sight distance is greater than 1000 feet, which is the minimum passing sight distance for a 60 mph highway recommended by the MUTCD, was also compared to control for unsafe events that would have occurred in no-passing zones had the centerline been striped per MUTCD guidance. The mean values of the initial distance and TTC variables were compared using a *t*-test, and the proportions of unsafe passes were compared using a chi-square contingency test. All tests were performed at the 95% confidence level. The results are summarized in Table 4.7 and Table 4.8; significant differences are denoted as indicated in the footnotes of each table.

**Table 4.7** Passing safety characteristics on horizontal curves

	500 ft			1000 ft		
	Left	Straight	Right	Left	Straight	Right
Initial Distance <sup>α</sup> (to oncoming vehicle, in feet)	3846.4	4008.9	3970.1	3844.1	4035.9	4025.9
Initial Distance <sup>β</sup> (SD > 1000 feet, in feet)	3903.9	4019.2	4011.5	3882.0	4052.4	4072.8
Time to Contact <sup>α</sup> (in seconds)	10.6	12.8†	12.1†	10.7	13.1†	12.7†
Time to Contact <sup>β</sup> (SD > 1000 feet, in seconds)	11.0	12.4	12.4	10.9	12.6†	13.0†
Proportion of Unsafe Passes <sup>α</sup> (defined as TTC < 3 seconds)	0.106	0.116	0.089	0.115	0.110	0.089

<sup>α</sup>N = (217,249,135), (287,145,169)

<sup>β</sup>N = (195, 237, 123), (264, 137, 154)

Significant (*p* < 0.05) differences indicated by: \* > Right, † > Left

**Table 4.8** Passing safety characteristics on horizontal curves

	500 ft			1000 ft		
	Crest	Flat	Sag	Crest	Flat	Sag
Initial Distance <sup>α</sup> (to oncoming vehicle, in feet)	3858.2	3975.0	3963.5	3848.2	4159.4†‡	3875.2
Initial Distance <sup>β</sup> (SD > 1000 feet, in feet)	3932.5	3993.5	3984.7	3859.9	4213.9†‡	3908.5
Time to Contact <sup>α</sup> (in seconds)	10.9	11.6	13.2†	11.1	12.5	11.9
Time to Contact <sup>β</sup> (SD > 1000 feet, in seconds)	11.1	11.7	12.9	11.2	12.7†	11.9
Proportion of Unsafe Passes <sup>α</sup> (defined as TTC < 3 seconds)	0.109	0.125	0.072	0.124	0.096	0.101

<sup>α</sup>N = (156, 279, 166), (177, 157, 267)

<sup>β</sup>N = (127, 268, 160), (160, 150, 245)

Significant (*p* < 0.05) differences indicated by:

\* > Flat, † > Crest, ‡ > Sag

When the road was flat for at least 1000 feet from pass initiation, the average distance to the oncoming vehicle at initiation was 4159.4 feet compared with 3848.2 feet when there was a crest curve and 3875.2 feet when there was a sag curve. When the sight distance was more than 1000 feet, the average time to contact of 12.7 seconds was higher when the road was flat compared with 11.2 seconds when the road had a crest curve, which corresponds to the higher initial

distance. When the road had a sag curve within 500 feet of initiation of the pass, the time to contact averaged 13.2 seconds, which was higher than the average of 10.9 seconds when there was a crest curve in the early portion of the pass, although this difference diminished when sight distance was greater than 1000 feet. The higher average time to contact in both of these cases did not correspond to a significant difference in the proportions of unsafe passes.

#### 4.5. Data Analysis – Second Stage

##### 4.5.1. Effects of Guardrails on Passing Behavior

The effects of guardrails on passing behavior were examined by comparing the number and characteristics of pass attempts on the Seward Highway section only in order to isolate the effects of the guardrail from the confounding effects of geometry. To assess how the presence of a guardrail affects a driver’s choice to pass, the number of pass attempts and the proportion of completed versus aborted passes were compared between conditions. To assess how the presence of a guardrail affects the safety outcomes of passes, the average TTC for attempted and completed passes and the proportion of safe (TTC > 3 seconds) versus unsafe (TTC < 3 seconds) passes were compared between conditions. The results are summarized in Table 4.9; as shown, none of the probabilities ( $p$ ) were significant at a 0.05 significance level.

**Table 4.9** Effects of guardrail on passing behavior

		Guardrail		p
		No	Yes	
Pass Attempts	Attempts/ Participant	2.61	2.45	0.80
	Completed	72	74	0.16
	Aborted	14	7	
	TTC (s)	3.53	3.48	0.88
Completed Passes	Passes/ Participant	2.40	2.47	0.82
	Safe	32	31	0.87
	Unsafe	40	43	
	TTC (s)	3.05	3.10	0.88

For the 33 participants that attempted to pass on the Seward Highway section, the average number of attempts with no guardrail present was 2.61, and the average number of attempts with a guardrail present was 2.45. These averages were compared with a paired  $t$ -test and were not found to be different at a significance of  $p < 0.05$ . In the no-guardrail condition, 72 passes were completed and 14 were aborted; in the presence of a guardrail, 74 passes were completed and 7 were aborted. These proportions were compared using Fisher’s exact test and were not found to be different at a significance of  $p < 0.05$ . The average final TTC for pass attempts in the no-guardrail condition was 3.53 seconds, and the average final TTC for pass attempts in the

presence of a guardrail was 3.48 seconds. These averages were compared with a  $t$ -test and were not found to be different at a significance of  $p < 0.05$ .

For the 30 participants that completed at least one pass on the Seward Highway section, the average number of completed passes with no guardrail present was 2.40, and the average number of passes with a guardrail present was 2.47. These averages were compared with a paired  $t$ -test and were not found to be different at a significance of  $p < 0.05$ . In the no-guardrail condition, 32 passes were safe and 40 were unsafe; in the presence of a guardrail, 31 passes were safe and 43 were unsafe. These proportions were compared using Fisher’s exact test and were not found to be different at a significance of  $p < 0.05$ . The average final TTC for completed passes in the no-guardrail condition was 3.05 seconds, and the average final TTC for passes in the presence of a guardrail was 3.10 seconds. These averages were compared with a  $t$ -test and were not found to be different at a significance of  $p < 0.05$ .

#### 4.5.2. Effects of Guardrails on Collision Avoidance

The effects of guardrails on collision avoidance were examined by comparing the proportion of drivers that collided with the oncoming vehicle and the distance that the drivers moved toward the edge of the roadway (measured from the center of the driver’s travel lane) under the conditions of no guardrail and the presence of a guardrail. The results from the collision avoidance simulation are summarized in Table 4.10.

**Table 4.10** Effects of guardrail on collision avoidance

	Guardrail		p
	No	Yes	
Collision	4	16	0.0005
No Collision	20	8	
Lane Deviation (ft)	7.53	4.71	0.01

In the no-guardrail condition, 4 participants collided with the oncoming vehicle and 20 participants avoided a collision; in the presence of a guardrail, 16 participants collided with the oncoming vehicle and 8 participants avoided a collision. These proportions were compared using Fisher’s exact test and were significantly different at a significance of  $p < 0.05$ . In the no-guardrail condition, the average lane deviation was 7.53 feet, and in the presence of a guardrail, the average lane deviation was 4.71 feet. These averages were compared using the Mann-Whitney  $U$  test and were significantly different at a significance of  $p < 0.05$ .

These results indicate that the presence of guardrail may increase the occurrences of head-on collisions because drivers do not correctly perceive the risks involved in colliding with a vehicle versus colliding with a guardrail. While it is clear that colliding with guardrail is preferable given the undesirable options available, drivers may not have time to process the risks with the urgency required to avoid a collision.

## CHAPTER 5. CONCLUSIONS

This study presented and evaluated the effects of roadway curvature on passing maneuvers along real-world rural two-lane highways in Alaska using in-field observations of passing maneuvers and a driving simulator. The following discussion includes the practical implications of the passing behavior and collision avoidance portions of this study as well as the study's limitations.

### 5.1. Passing Behavior

The passing maneuver is one of the most complex maneuvers in rural highway driving and is consequently difficult to assess. Existing models are based primarily on vehicle speeds and available gaps, and fail to directly account for road geometry. Previous studies have shown that roadway geometry affects driver willingness to accept a gap and initiate a pass, although these studies did not consider vertical curvature or specify directionality in the horizontal curvature. The present study showed that horizontal curvature, vertical curvature, and slope have significant effects on a driver's choice to pass, but the presence of a guardrail was not found to have a significant effect. The in-field study corroborates previous studies that indicate higher rates of speed undertaken by passing and impeding vehicles than is assumed in the AASHTO and MUTCD standards.

The results of the field study showed that on all three highway segments (Parks, Seward, and Sterling), the speeds of passing vehicles are approximately 10 mph over the posted speed limit. The average initial speed of the vehicles being passed were approximately 2 mph over the speed limit. Standard deviations for both passing and impeding vehicles ranged from 3 mph to 7 mph. This has significant implications for the design of passing zones, as the AASHTO and MUTCD standards assume that the speed of passing vehicles does not exceed the posted speed limit. Furthermore, the field study revealed a significant number of early-start and late-finish passes, where a portion of the passing maneuver occurred outside of the designated passing area. The rate of early-start passes was higher for the Parks Highway segment; the rate of late-finish passes was higher for the Seward Highway segment. Early-start and late-finish passes tended to occupy the opposing lane for more time than passes that were compliant and occurred completely within the confines of the passing zone.

The results of the simulator study have practical implications for microsimulation of rural highways, highway design, and highway safety. After the effects of geometric variables on passing choice are better understood and modeled more precisely, microsimulation can incorporate these effects to model more accurately the expected locations of passes. The findings likely have ramifications for highway design because highway capacity could be modeled more effectively, and the locations of passing zones and passing lanes could be designed accordingly. Additionally, the ability to accurately predict where passing is most likely to occur on a section of highway could have implications for prioritization of safety treatments and signage.

Horizontal and vertical curvature were both shown to have significant effects on the characteristics of passing maneuvers including the speed of the passing vehicle, the total time and distance of the maneuvers, and the distance between the passing vehicle and the impeding vehicle at initiation and termination of the maneuvers. These differences may have implications for capacity and safety analysis of rural two-lane highways. The implementation of improved models of vehicle trajectories during passing maneuvers may lead to more accurate microsimulation models of rural two-lane highways and would enable improved capacity

analyses, which could inform the design of passing zones and passing lanes. The distance to the impeding vehicle at the initiation and termination of a passing maneuver may have safety implications with regard to the risk of rear-end collisions and same-direction sideswipe collisions of the passing and impeding vehicles.

Despite differences in passing choice and passing maneuvers, roadway geometry was not shown to significantly affect the safety outcomes of passes. Although there were conditions in which average time to contact was different (e.g., lower when the road curved to the left than when straight or curved to the right, and higher when the road had a sag curve than when flat or had a crest curve), none of these differences corresponded to a significantly higher proportion of passes ending with an unsafe time to contact. The presence of a guardrail was also not shown to have a significant effect on the proportion.

## 5.2. Collision Avoidance

The results of the simulated collision avoidance experiment indicate that the presence of a guardrail may increase the occurrences of head-on collisions because drivers do not correctly perceive the risks involved in colliding with a vehicle versus colliding with guardrail. While it is clear that colliding with a guardrail is preferable given the undesirable options available, drivers may not have time to process the risks with the urgency required to avoid a collision.

This finding has implications for safety analysis of rural two-lane highways. If the presence of a guardrail significantly impedes the ability of drivers to safely avoid head-on collisions, this effect should be taken into account in the prioritization of safety projects. Though not tested as part of this study, safety features such as centerline rumble strips or centerline barriers may have a greater impact in reducing the prevalence of head-on collisions and reducing the average severity of collisions on roadway sections with guardrails; the use of additional signage (refer to the MUTCD, Chapter 2B.28 and Chapter 2C.45) is also recommended for consideration. This finding may have implications for lane width, shoulder width, and the lateral placement of the guardrail, but more research should be conducted to determine whether the impediment diminishes when the guardrail is farther from the centerline.

## 5.3. Study Limitations

One limitation of this study is that the orientation of the cameras in the field made it difficult or impossible to see if there was an oncoming vehicle in the opposing lane when a passing maneuver occurred, and if there was an oncoming vehicle, what its location was as the passing vehicle executed the passing maneuver. Without this information (effectively  $d_3$  in Equation 1), it would be imprudent to infer the total deviation from the design passing sight distances computed by AASHTO and MUTCD. However, the large difference between actual and assumed design speeds provides justification for local calibration. Another limitation of the field study is that for statistical validity, passing maneuvers were only categorized into compliant, early-start, and late-finish passes. No distinction was made between passes that were “on the fly” (i.e., a *flying* pass where the passing vehicle initiated the pass without having spent some previous amount of time following behind the impeding vehicle at a lower rate of speed) and passes that were *delayed*, requiring the passing vehicle to accelerate to passing speed to overtake the impeding vehicle. Further, no distinction was made between passes that included only one impeding vehicle and passes that overtook several vehicles in one maneuver. However, only a

few cases fell into each of these groups (i.e., flying passes and passing multiple vehicles), and their characteristics were not significantly different enough from the other passing types to be concerned about exclusion or re-categorization.

With respect to the simulator study, one limitation was that the use of real-world alignments for the simulation precluded an experimental design in which the horizontal and vertical curvature was systematically varied to isolate and infer effects. In doing so, variation was added to the test variables due to unknown interaction effects and possible order effects. An experiment with a track specifically designed with systematic changes in curvature should be conducted to validate and strengthen the results of this study.

Considering that the data for the simulator portion of the study were collected in a virtual environment, the developed passing choice model may not have predictive validity on real-world alignments. However, since the purpose of the model was to infer effects rather than to make predictions, the results are likely valid in terms of relative validity. Field studies should be used to validate these findings and calibrate any models developed for prediction on real-world highways. Similarly, the differences in visual perception and vehicle controls in the simulation likely lead to differences in passing maneuvers in the simulator versus in real-world driving, so the passing maneuver characterization may lack absolute validity. Again, the purpose of the characterization was to compare the relative effects of curvature, and the results are likely valid in terms of relative validity. Finally, perceived risk in a driving simulator is far less than in real-world driving because the consequences of crashing, which are potentially catastrophic in the real world, are nonexistent in the simulator. Therefore, the results of the passing safety and collision avoidance analyses should be viewed with these limitations in mind and should be validated using real-world data.

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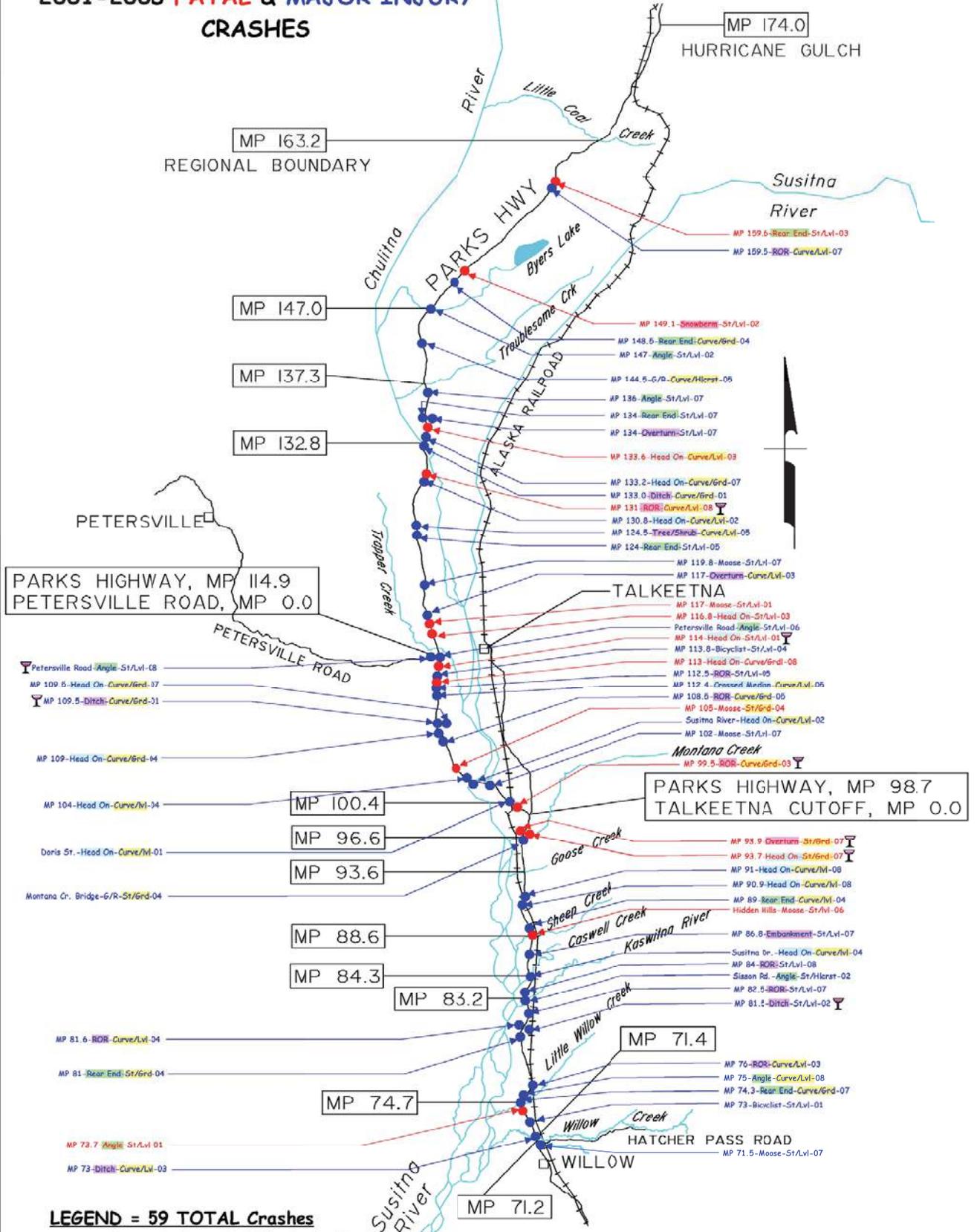
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## **APPENDIX A**

2001–2008 Fatal and Major Crashes on  
Parks, Seward, and Sterling Highways

# Parks Highway: MP 71 to MP 163

## 2001-2008 FATAL & MAJOR INJURY CRASHES



**LEGEND = 59 TOTAL Crashes**

- = FATAL CRASH (14) Alcohol Related (5)
  - = MAJOR INJURY CRASH (45) Alcohol Related (3)
  - = Curve and/or Grade (33)
  - = Head On, Crossed Median or Sideswipe (16)
  - = Run off the Road (19)
  - = Angle or Rear End (14)
- (Also 2 Ped/Bike, 6 Moose & 2 G/R)

PARKS HIGHWAY  
MP 71.2 to 163.2  
WILLOW CREEK to LITTLE COAL CREEK

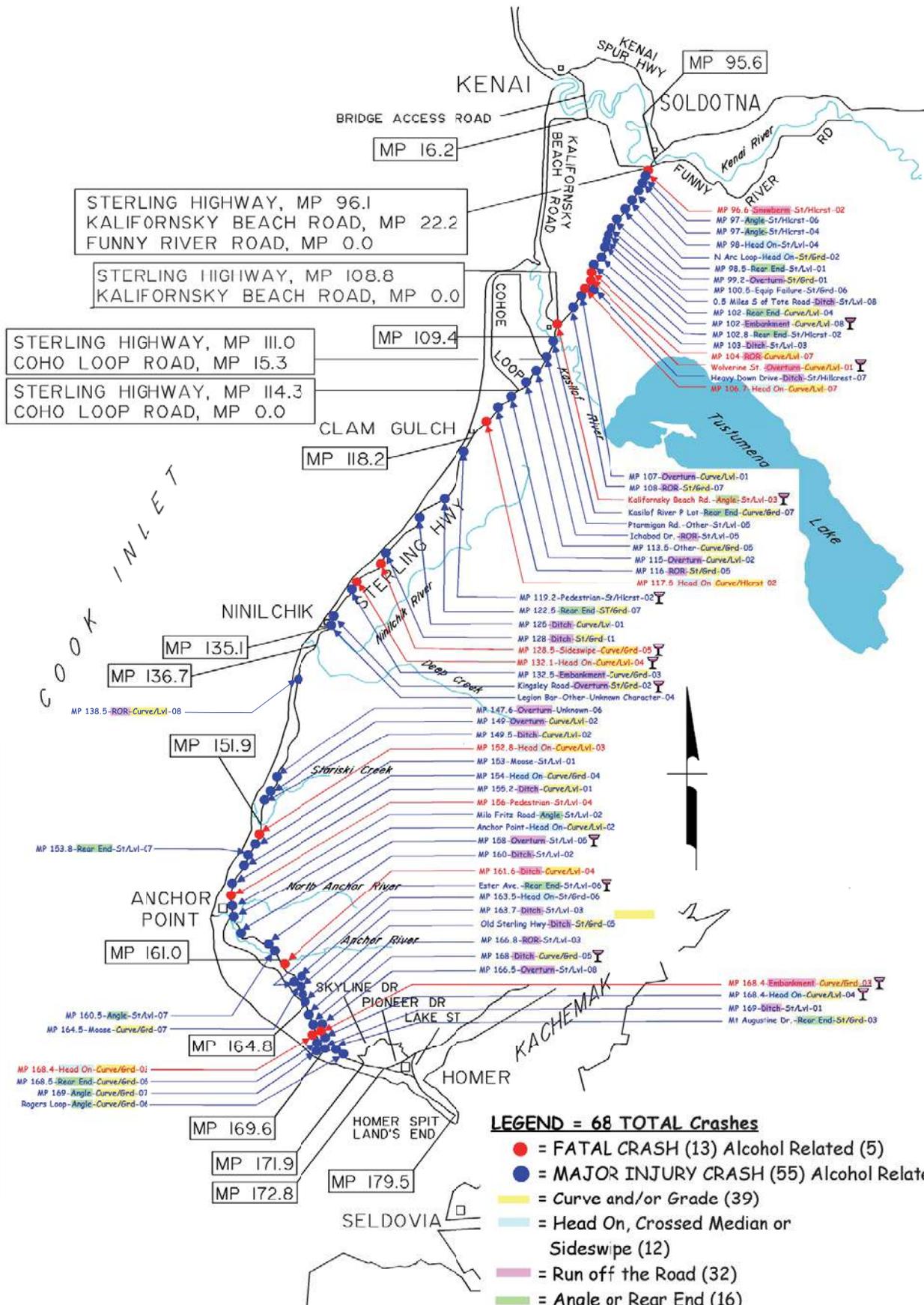
State of Alaska  
Department of Transportation & Public Facilities  
Central Region  
Traffic, Safety & Utilities Section

**Map #1: Parks Highway  
Milepost 71 to Milepost 163**

Drawn By: RFM  
Scale: None

Date: 3/23/2010  
Page





**Sterling Highway: MP 96 to MP 170  
2001-2008 FATAL & MAJOR INJURY  
CRASHES**

STERLING HIGHWAY  
MP 95.9 to 179.5  
KENAI RIVER to LAND'S END

- LEGEND = 68 TOTAL Crashes**
- = FATAL CRASH (13) Alcohol Related (5)
  - = MAJOR INJURY CRASH (55) Alcohol Related (7)
  - = Curve and/or Grade (39)
  - = Head On, Crossed Median or Sideswipe (12)
  - = Run off the Road (32)
  - = Angle or Rear End (16)
- (Also 2 Ped, 2 Moose & 4 Others)

State of Alaska Department of Transportation & Public Facilities Central Region Traffic, Safety & Utilities Section	
<b>Map #7: Sterling Highway South of Soldotna Milepost 96 to Milepost 170</b>	
Drawn By: RFM	Date: 3/23/2010
Scale: None	Page